Solid Waste Management and Greenhouse Gases

A Life-Cycle Assessment of Emissions and Sinks


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SOLID WASTE MANAGEMENT AND GREENHOUSE GASES
A Life-Cycle Assessment of Emissions and Sinks

3rd EDITION

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TABLE OF CONTENTS

TABLE OF EXHIBITS

EXECUTIVE SUMMARY: BACKGROUND AND FINDINGS

In the 21st century, management of municipal solid waste (MSW) continues to be an important environmental challenge facing the United States. In 2003, the United States generated 236.2 million tons[1] of MSW, an increase of 15 percent over 1990 generation levels and 168 percent over 1980 levels.[2] Climate change is also a serious issue, and the United States is embarking on a number of voluntary actions to reduce the emissions of greenhouse gases (GHGs) that can intensify climate change. By presenting material-specific GHG emission factors for various waste management options, this report examines the interrelationship between MSW management and climate change.

Among the efforts to slow the potential for climate change are measures to reduce emissions of carbon dioxide (CO_2) from energy use, decrease emissions of methane (CH_4) and other non-carbon-dioxide GHGs, and promote long-term storage of carbon in forests and soil. Management options for MSW provide many opportunities to affect these processes, directly or indirectly. This report integrates information on the GHG implications of various management options for some of the most common materials in MSW. To EPA's knowledge, this work represents the most complete national study on GHG emissions and sinks from solid waste management practices. The report's findings may be used to support a variety of programs and activities, including voluntary reporting of emission reductions from waste management practices.

ES.1 GHGs AND CLIMATE CHANGE

Climate change is a serious international environmental concern and the subject of much research. Many, if not most, of the readers of this report will have a general understanding of the greenhouse effect and climate change. However, for those who are not familiar with the topic, a brief explanation follows.[3]

A naturally occurring shield of "greenhouse gases" (primarily water vapor, CO_2, CH_4, and nitrous oxide), comprising 1 to 2 percent of the Earth's atmosphere, absorbs some of the solar radiation that would otherwise be radiated into space and helps warm the planet to a comfortable, livable temperature range. Without this natural "greenhouse effect," the average temperature on Earth would be approximately -2 degrees Fahrenheit, rather than the current 57 degrees Fahrenheit.[4]

Many scientists are concerned about the significant increase in the concentration of CO_2 and other GHGs in the atmosphere. Since the preindustrial era, atmospheric concentrations of CO_2 have increased by nearly 30 percent and CH_4 concentrations have more than doubled. There is a growing international scientific consensus that this increase has been caused, at least in part, by human activity, primarily the

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[1] All references to tonnage of waste in this report are in short tons. All references to tons of carbon or CO_2 equivalent are in metric tons (i.e., MTCE per short ton of material).

[2] EPA Office of Solid Waste, Municipal Solid Waste in the United States: 2003 Facts and Figures, EPA (2005), p. 2.

[3] For more detailed information on climate change, please see the 2005 *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*, available online at: http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html (September 2005); and *Climate Change 2001: The Scientific Basis* (J.T. Houghton, et al., eds. Intergovernmental Panel on Climate Change [IPCC]; published by Cambridge University Press, 2001). To obtain a list of additional documents addressing climate change, access EPA's global warming Web site at http://yosemite.epa.gov/oar/globalwarming.nsf/content/index.html.

[4] Climate Change 2001: The Scientific Basis, op. cit., pp. 89-90.

burning of fossil fuels (coal, oil, and natural gas) for such activities as generating electricity and driving cars.[5]

Moreover, in international scientific circles a consensus is growing that the buildup of CO_2 and other GHGs in the atmosphere will lead to major environmental changes such as (1) rising sea levels that may flood coastal and river delta communities; (2) shrinking mountain glaciers and reduced snow cover that may diminish fresh water resources; (3) the spread of infectious diseases and increased heat-related mortality; (4) possible loss in biological diversity and other impacts on ecosystems; and (5) agricultural shifts such as impacts on crop yields and productivity.[6] Although reliably detecting the trends in climate due to natural variability is difficult, the most accepted current projections suggest that the rate of climate change attributable to GHGs will far exceed any natural climate changes that have occurred during the last 1,000 years.[7]

Many of these changes appear to be occurring already. Global mean surface temperatures already have increased by about 1 degree Fahrenheit over the past century. A reduction in the northern hemisphere's snow cover, a decrease in Arctic sea ice, a rise in sea level, and an increase in the frequency of extreme rainfall events all have been documented.[8]

Such important environmental changes pose potentially significant risks to humans, social systems, and the natural world. Many uncertainties remain regarding the precise timing, magnitude, and regional patterns of climate change and the extent to which mankind and nature can adapt to any changes. It is clear, however, that changes will not be easily reversed for many decades or even centuries because of the long atmospheric lifetimes of GHGs and the inertia of the climate system.

ES.2 CLIMATE CHANGE INITIATIVES IN THE UNITED STATES

In 1992, world leaders and citizens from some 200 countries met in Rio de Janeiro, Brazil, to confront global ecological concerns. At this "Earth Summit," 154 nations, including the United States, signed the United Nations Framework Convention on Climate Change (UNFCCC), an international agreement to address the danger of global climate change. The objective of the Convention was to stabilize GHG concentrations in the atmosphere over time at a level at which manmade climate disruptions would be minimized.

By signing the Convention, countries made a voluntary commitment to reduce GHGs or take other actions to stabilize emissions of GHGs. All Parties to the Convention were required to develop and periodically update national inventories of their GHG emissions. The United States ratified the Convention in October 1992. One year later, the United States issued its *Climate Change Action Plan* (CCAP), which calls for cost-effective domestic actions and voluntary cooperation with states, local governments, industry, and citizens to reduce GHG emissions.

In order to achieve the goals outlined in the *Climate Change Action Plan*, EPA initiated several voluntary programs to realize the most cost-effective opportunities for reducing emissions. For example, in 1994 EPA created the Landfill Methane Outreach Program, which aims to reduce landfill CH_4 emissions by facilitating the development of projects that use landfill gas to produce energy.[9] In the same year, EPA introduced the Climate and Waste Program to capture the climate benefits of a broader set of waste-related initiatives (e.g., recycling, source reduction). In 2001 EPA started the Green Power Partnership. This partnership aids organizations that want to obtain some or all of their power from

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[5] *Ibid.*, p. 7.
[6] J.J. McCarthy, et al., eds. 2001. *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. IPCC. Cambridge University Press. pp. 9-13.
[7] Climate Change 2001: The Scientific Basis, op. cit., p. 2.
[8] *Ibid.*, p. 4.
[9] Available at the U.S. Environmental Protection Agency's Landfill Methane Outreach Program website: http://www.epa.gov/lmop. Toll-free hotline number: 800-782-7937.

renewable energy sources, including landfill gas. The program has more than 500 partners, whose green power purchasing commitments now exceed two million megawatt-hours.

To date, EPA's voluntary partnership programs for climate protection have achieved substantial environmental results. In 2004 alone, these programs reduced GHG emissions by 57 million metric tons of carbon equivalent (MMTCE)—the equivalent of eliminating the annual emissions from approximately 45 million cars.[10] In addition, substantial CH_4 emission reductions—estimated at more than one MMTCE for the period from 1999–2000—are being obtained as an ancillary benefit of Clean Air Act (CAA) regulatory requirements that were promulgated in 1996, limiting emissions from landfills.

Many corporations that are concerned about climate change and wish to take action have joined EPA's Climate Leaders program. Participating corporations set reduction targets for themselves and agree to report their emissions annually and monitor progress toward their target. Participants come from a broad range of sectors, including energy and oil, pharmaceuticals, banking, high-tech, and manufacturing.[11] As of April 2006, there were 86 Climate Leaders, 46 of whom had set reduction targets. Together, these 79 companies account for about 8 percent of U.S. GHG emissions; the targets, if met, will prevent emissions of more than eight MMTCE per year.[12]

The U.S. Department of Energy (DOE) administers a voluntary GHG reporting program under section 1605(b) of the Energy Policy Act of 1992. This program enables companies and other entities to report their GHG emissions and to gain recognition for reductions they have implemented, including reductions through MSW management innovations. The 1605(b) program is currently finalizing revised guidelines and provisions.[13]

There has been significant action on the regional level as well. The six New England states (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont) joined with the eastern Canadian provinces in 2001 to write the New England Governors/Eastern Canadian Premiers (NEG/ECP) Climate Change Action Plan. The Governors and Premiers agreed to commit their states and provinces to write and implement action plans that will achieve the goals of reducing emissions to 1990 levels by 2010, and to 10 percent below 1990 emissions by 2020.[14] Some of these states were among the first to write climate change action plans, as a result of commitment to the NEG/ECP goals. Seven northeastern states (plus four observer states) have joined together to form the Regional Greenhouse Gas Initiative (RGGI), which, when it comes into effect, will be a cap-and-trade system for power plant GHG emissions, the first of its kind in the US. The West Coast Governors' Global Warming Initiative was started by the Governors of California, Oregon, and Washington in 2003. The goals of the initiative include combining purchasing power to improve the efficiency of vehicle fleets and improving appliance efficiency standards. They are considering the creation of a regional cap-and-trade system. California is also contemplating a cap-and-trade system that would include not just power plants, but also other stationary sources of GHG emissions, such as semiconductor manufacturers.

Meanwhile, an increasing number of states have instituted their own voluntary actions to reduce emissions. Forty-two states and Puerto Rico have inventoried their GHG emissions. Twenty-eight states

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[10] EPA Press Release, "10 Billion Saved on Energy Bills," 4 October 2005; car equivalent calculation available online at the U.S. Climate Technology Cooperation Gateway's Greenhouse Gas Equivalencies Calculator: http://www.usctcgateway.net/tool/.

[11] Available at the EPA's Climate Leaders website: http://www.epa.gov/climateleaders

[12] John Millet, "Five Climate Leaders Companies Reach Their Greenhouse Gas Reduction Goals," U.S. Environmental Protection Agency press release. 18 January 2006.

[13] DOE, "Enhancing DOE's Voluntary Reporting of Greenhouse Gases (1605(b)) Program." Department of Energy. Available online at: http://www.pi.energy.gov/enhancingGHGregistry

[14] The New England Governors/Eastern Canadian Premiers website: http://www.negc.org/premiers.html

and Puerto Rico have completed or initiated state action plans, which outline steps to reduce emissions.[15] Twenty-five of these action plans have incorporated the reduction of waste into their GHG mitigation strategies. Finally, at least 11 states—including California, Illinois, New Hampshire, and Wisconsin—are in the process of establishing GHG registries, which enable companies and other entities to report voluntary emission reductions.[16]

Many states are engaging in further study of climate change implications and, in some cases, enacting legislation. For example, 22 states and the District of Columbia have renewable portfolio standards (RPS), requiring that electricity producers obtain a certain amount of their power from renewable sources. In most of these states, waste-to-energy facilities and landfill gas are permitted energy sources.

Oregon recently created its Strategy for Greenhouse Gas Reductions, outlining recommended actions to reduce GHG emissions at the state level. Ten of these actions fall under the category "Materials Use, Recovery, and Waste Disposal" and include such strategies as increasing "Bottle Bill" refunds to 10 cents from 5 and widening the scope to include all beverage containers except milk.

Cities and towns also are taking action. More than 160 municipalities in the United States have joined the Cities for Climate Protection (CCP) campaign run by ICLEI (Local Governments for Sustainability). CCP members agree to inventory their GHG emissions, set a reduction target, write an action plan to reduce emissions, and implement the plan. One of the key sectors that the CCP program focuses on is waste, and many cities have taken action on this issue. For example, Seattle has increased its recycling rate, reduced landfill CH_4 emissions, and banned recyclables from garbage.

ES.3 MUNICIPAL SOLID WASTE AND GHG EMISSIONS

What does MSW have to do with rising sea levels, higher temperatures, and GHG emissions? For many wastes, the materials in MSW represent what is left over after a long series of steps: (1) extraction and processing of raw materials; (2) manufacture of products; (3) transportation of materials and products to markets; (4) use by consumers; and (5) waste management.

Virtually every step along this "life cycle" impacts GHG emissions. Solid waste management decisions can reduce GHGs by affecting one or more of the following:

(1) Energy consumption (specifically, combustion of fossil fuels) associated with making, transporting, using, and disposing the product or material that becomes a waste.

(2) Nonenergy-related manufacturing emissions, such as the CO_2 released when limestone is converted to lime (e.g., steel manufacturing).

(3) CH_4 emissions from landfills where the waste is disposed.

(4) CO_2 and nitrous oxide (N_2O) emissions from waste combustion.

(5) Carbon sequestration, which refers to natural or manmade processes that remove carbon from the atmosphere and store it for long periods or permanently.

The first four mechanisms *add* GHGs to the atmosphere and contribute to global warming. The fifth—carbon sequestration—*reduces* GHG concentrations by removing CO_2 from the atmosphere.

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[15] EPA's Global Warming—Actions, "State" webpage. Available at: http://yosemite.epa.gov/oar/globalwarming.nsf/content/ActionsState.html.

[16] Progressive Policy Institute, State Greenhouse Gas Registries, 5 September 2003. Available at: http://www.ppionline.org/ppi_ci.cfm?knlgAreaID=116&subsecID=900039&contentID=251287

Forest growth is one mechanism for sequestering carbon; if more biomass is grown than is removed (through harvest or decay), the amount of carbon stored in trees increases, and thus carbon is sequestered.

Different wastes and waste management options have different implications for energy consumption, CH_4 emissions, and carbon sequestration. Source reduction and recycling of paper products, for example, reduce energy consumption, decrease combustion and landfill emissions, and increase forest carbon sequestration.

ES.4 GENESIS AND APPLICATIONS OF THE REPORT

Recognizing the potential for source reduction and recycling of municipal solid waste to reduce GHG emissions, EPA included a source reduction and recycling initiative in the original 1994 Climate Change Action Plan and set an emission reduction goal based on a preliminary analysis of the potential benefits of these activities. It was clear that a rigorous analysis would be needed to gauge more accurately the total GHG emission reductions achievable through source reduction and recycling.

That *all* of the options for managing MSW should be considered also became clear. By addressing a broader set of MSW management options, a more comprehensive picture of the GHG benefits of voluntary actions in the waste sector could be determined, and the relative GHG impacts of various waste management approaches could be assessed. To this end, EPA launched a major research effort, the results of which were published in the first edition of this report in September 1998. A second edition of the report was published in May 2002. This third edition of the report includes additional materials and incorporates updated data affecting some of the material-specific results. The emission factors[17] presented will continue to be updated and improved as more data become available. The latest emission factors, reflecting these ongoing revisions, can be found on EPA's "Measuring Greenhouse Gas Emissions from Waste" website.[18]

The primary application of the GHG emission factors in this report is to support waste-related decisionmaking in the context of climate change. By quantifying the climate impacts of waste management decisions, the factors in this report enable municipalities, companies, and other waste management decisionmakers to measure the benefits of their actions. In recent years, the emission factors have been applied for this purpose in a number of ways. In conjunction with the DOE, EPA has used these estimates to develop guidance for voluntary reporting of GHG reductions, as authorized by Congress in Section 1605(b) of the Energy Policy Act of 1992. However, under the new, more rigorous 1605(b) reporting guidelines, emissions reductions from solid waste management practices would be reported separately under "other indirect emissions" and not included in the main corporate inventory.

Other applications have included quantifying the GHG reductions from voluntary programs aimed at source reduction and recycling, such as EPA's WasteWise, Pay-As-You-Throw, and Coal Combustion Products Partnership (C^2P^2) programs. EPA also has worked with the Climate Neutral Network to develop company-specific GHG "footprints" for the network's member companies, who have pledged to become GHG "neutral" through emission reductions or offset activities.

Currently, Climate Leaders does not record GHG emissions reductions from the purchase of recycled-content paper or the recycling of waste paper in a Partners' inventory. Climate Leaders focuses on corporate-level GHG inventory emissions calculations and reporting. Calculating GHG emission reductions from recycling uses a project-level approach which can involve a high level of uncertainty from the calculation of avoided emissions. The approach used to calculate a corporate GHG emissions inventory uses activity data, such as fuel consumption, which allow for a higher level of accuracy than the

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[17] An amount of waste (in short tons) is multiplied by an emission factor (in MTCE/ton) to yield GHG emissions in MTCE. Each emission factor is specific to a particular waste management practice and to a particular material type.
[18] EPA's Global Warming—Waste, "Measuring Greenhouse Gas Emissions from Waste" webpage. Available at: http://www.epa.gov/mswclimate

avoided emissions approach. Therefore, Climate Leaders does not currently count these GHG emissions reductions from avoided emissions. However, as the methodology for calculating project level reductions from the use of recycled paper and the recycling of waste paper evolves, EPA will reconsider recognizing Partners for these activities. Since the reductions from improved materials management activities do lead to global reductions in GHG emissions -- EPA encourages Partners to continue efforts in promoting these programs and measuring their impact.

The international community has shown considerable interest in using the emission factors—or adapted versions—to develop GHG emission estimates for non-U.S. solid waste streams.[19] For example, Environment Canada and Natural Resources Canada recently employed EPA's life-cycle methodology and components of its analysis to develop a set of Canada-specific GHG emission factors to support analysis of waste-related mitigation opportunities.[20]

Additionally, EPA worked with ICLEI to incorporate GHG emission factors into its municipal GHG accounting software. Currently, more than 600 communities worldwide participate in ICLEI's Cities for Climate Protection Campaign, which helps them establish a GHG emission reduction target and implement a comprehensive local action plan designed to achieve that target. Currently, EPA is exploring other options for broadening the use of its research internationally.

To make it easier for organizations to use these emission factors, EPA created the Waste Reduction Model (WARM), the Recycled Content (ReCon) Tool, and the Durable Goods Calculator (DGC). All of these tools are discussed in more detail in Section ES.7, below.

ES.5 THE IMPACT OF MUNICIPAL SOLID WASTE MANAGEMENT ON GHG EMISSIONS

To measure the GHG impacts of MSW, EPA first decided which wastes to analyze. The universe of materials and products found in MSW was surveyed and those that are most likely to have the greatest impact on GHGs were identified. These determinations were based on (1) the quantity generated; (2) the differences in energy use for manufacturing a product from virgin versus recycled inputs; and (3) the potential contribution of materials to CH_4 generation in landfills. By this process, EPA limited the analysis to the following 21 single-material items:[21]

- Three categories of metal:
  - Aluminum Cans;
  - Steel Cans;
  - Copper Wire;
- Glass;
- Three types of plastic:
  - HDPE (high-density polyethylene);
  - LDPE (low-density polyethylene);
  - PET (polyethylene terephthalate);

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[19] Note that waste composition and product life cycles vary significantly among countries. This report may assist other countries by providing a methodological framework and benchmark data for developing GHG emission estimates for their solid waste streams.

[20] Environment Canada. 2001. *Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions*. Prepared by ICF Consulting, Torrie-Smith Associates, and Enviros-RIS.

[21] The following materials are new to this edition: copper wire, clay bricks, concrete, fly ash, tires, carpet, and personal computers.

- Six categories of paper products:
  - Corrugated Cardboard;
  - Magazines/Third-class Mail;
  - Newspaper;
  - Office Paper;
  - Phonebooks;
  - Textbooks;
- Two types of wood products:
  - Dimensional Lumber;
  - Medium-density Fiberboard;
- Food Discards;
- Yard Trimmings;
- Clay Bricks;
- Concrete;
- Fly Ash; and
- Tires.

EPA's researchers also included two products that are composites of several materials:

- Carpet; and
- Personal Computers.

The foregoing materials constitute more than 65 percent, by weight, of MSW, as shown in Exhibit ES-1 (this figure excludes clay bricks, concrete, copper wire, fly ash, and medium-density fiberboard, which were not included in the waste characterization report cited here).[22]

In addition to the materials listed above, EPA examined the GHG implications of managing mixed plastics, mixed metals, mixed organics, mixed recyclables, mixed MSW, and three definitions of mixed paper. Each of these mixed categories is summarized below.

- *Mixed plastics* are composed of HDPE, LDPE, and PET and are estimated by taking a weighted average of the 2003 recovery rates for these three plastic types.
- *Mixed metals* are composed of steel cans and aluminum cans and are estimated by taking a weighted average of the 2003 recovery rates for these two metal types.
- *Mixed organics* are a weighted average of food discards and yard trimmings, using generation rates for 2003.
- *Mixed recyclables* are materials that are typically recycled. As used in this report, the term includes the items listed in Exhibit ES-1, except food discards and yard trimmings. The emission factors reported for mixed recyclables represent the average GHG emissions for these materials, weighted by the tonnages at which they were recycled in 2003.

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[22] Note that these data are based on national averages. The composition of solid waste varies locally and regionally; local or state-level data should be used when available.

- *Mixed MSW* comprises the waste material typically discarded by households and collected by curbside collection vehicles; it does not include white goods (e.g., refrigerators, toasters) or industrial waste. This report analyzes mixed MSW on an "as-disposed" (rather than "as-generated") basis.
- *Mixed paper* is recycled in large quantities and is an important class of scrap material in many recycling programs. Presenting a single definition of mixed paper is difficult, however, because recovered paper varies considerably, depending on the source. For purposes of this report, EPA identified three categories of mixed paper according to the dominant source—broad (includes most categories of recyclable paper products), office, and residential (see Exhibit 3-2 for definitions of mixed paper categories).

The EPA researchers developed a streamlined life-cycle inventory for each of the selected materials. The analysis is streamlined in the sense that it examines GHG emissions only and is not a comprehensive environmental analysis of all emissions from municipal solid waste management options.[23]

EPA focused on those aspects of the life cycle that have the potential to emit GHGs as materials change from their raw states to products and then to waste. Exhibit ES-3 shows the steps in the life cycle at which GHGs are emitted, carbon sequestration is affected, and utility energy is displaced. As shown, EPA examined the potential for these effects at the following points in a product's life cycle:

- Raw material acquisition (fossil fuel energy and other emissions, and changes in forest carbon sequestration);

Exhibit ES-1
U.S. Generation of MSW For Materials in This Report

Material	MSW Generation by Weight (percent)
Aluminum Cans	0.6%
Steel Cans	1.1%
Copper Wire	N/A
Glass	4.5%
HDPE	1.6%
LDPE	1.3%
PET	0.9%
Corrugated Cardboard	12.6%
Magazines/Third-class Mail	3.2%
Newspaper	5.4%
Office Paper	3.0%
Phonebooks	0.3%
Textbooks	0.4%
Dimensional Lumber[a]	3.5%
Medium-density Fiberboard	N/A
Food Discards	11.0%
Yard Trimmings	12.1%
Carpet	1.2%
Personal Computers	N/A
Clay Bricks	N/A
Concrete	N/A
Fly Ash	N/A
Tires	2.0%
TOTAL	**64.8%**

[a] Listed in Municipal Solid Waste in the United States: 2003 Facts and Figures as "Wood—Containers and Packaging. Source: EPA. 2005. Municipal Solid Waste in the United States: 2003 Facts and Figures, EPA 530-F-05-003.

[23] EPA's Office of Research and Development (ORD) performed a more extensive application of life-cycle assessment for various waste management options for MSW. A decision support tool (DST) and life-cycle inventory (LCI) database for North America have been developed with funding by ORD through a cooperative agreement with the Research Triangle Institute (RTI) (CR823052). This methodology is based on a multimedia, multipollutant approach and includes analysis of GHG emissions as well as a broader set of emissions (air, water, and waste) associated with MSW operations. The LCI database is expected to be released in the summer of 2006. The website address for further information is: http://www.rti.org/, then search the term "DST."

- Manufacturing (fossil fuel energy emissions); and
- Waste management (CO_2 emissions associated with composting, nonbiogenic CO_2 and N_2O emissions from combustion, and CH_4 emissions from landfills); these emissions are offset to some degree by carbon storage in soil and landfills, as well as avoided utility emissions from energy recovery at combustors and landfills.

At each point in the material life cycle, EPA also considered transportation-related energy emissions. Estimates of GHG emissions associated with electricity used in the raw materials acquisition and manufacturing steps are based on the nation's current mix of energy sources,[24] including fossil fuels, hydropower, and nuclear power. However, when estimating GHG emission reductions attributable to utility emissions avoided, the electricity use displaced by waste management practices is assumed to be 100 percent fossil-derived.[25]

Improvements to the New Edition

This report is the third edition of *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*. This edition includes the following improvements:

- Develops emission factors for seven new material types: copper wire, clay bricks, concrete, fly ash, tires, carpet, and personal computers;
- Incorporates new energy data into calculations of utility offsets;
- Updates U.S. landfill gas collection characteristics to reflect the latest values from the U.S. Greenhouse Gas Inventory;
- Revises carbon coefficients and fuel use for national average electricity generation;
- Includes a discussion of emerging issues in the area of climate change and waste management;
- Includes a chapter on the energy reduction benefits of solid waste management.
- Provides an updated list of suggested proxy values for voluntary reporting of GHG emission reductions;
- Includes a discussion of open-loop recycling, as it relates to EPA's factors for fly ash, carpet, personal computers, and mixed paper;
- Adds retail transport to the methodology;
- Updates the current mix of recycled/virgin inputs for various materials; and
- Includes an updated analysis of forest carbon sequestration and moves the discussion into the recycling chapter.

These changes and/or revisions are described in more detail throughout the report and in Appendix C.

EPA did not analyze the GHG emissions typically associated with consumer use of products because the primary concern of this report was end-of-life management. Although the consumer-use stage of life can in some cases (e.g., personal computers) account for significant energy consumption, the energy consumed during use would be approximately the same whether the product was made from virgin or recycled inputs.

To apply the GHG estimates developed in this report, one must compare a baseline scenario with an alternative scenario, on a life-cycle basis. For example, one could compare a baseline scenario, where 10 tons of office paper are manufactured, used, and landfilled, to an alternative scenario, where 10 tons are manufactured, used, and recycled.

Exhibit ES-2 shows how GHG sources and sinks are affected by each waste management strategy. For example, the top row of the exhibit shows that source reduction[26] (1) reduces GHG

[24] The emissions are based on the current national grid mix, as opposed to regional grids.
[25] EPA adopted this approach based on suggestions from several reviewers who argued that fossil fuels should be regarded as the marginal fuel displaced by waste-to-energy and landfill gas recovery systems.
[26] The source reduction techniques the EPA researchers analyzed involve using less of a given product—e.g., by making aluminum cans with less aluminum ("lightweighting"); double-sided rather than single-sided photocopying;

emissions from raw materials acquisition and manufacturing; (2) results in an increase in forest carbon sequestration; and (3) does not result in GHG emissions from waste management. The sum of emissions (and sinks) across all steps in the life cycle represents net emissions.

Exhibit ES-2 Components of Net Emissions for Various MSW Management Strategies

MSW Management Strategy	GHG Sources and Sinks		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	Waste Management
Source Reduction	Decrease in GHG emissions, relative to the baseline of manufacturing	Increase in forest carbon sequestration (for organic materials)	No emissions/sinks
Recycling	Decrease in GHG emissions due to lower energy requirements (compared to manufacture from virgin inputs) and avoided process nonenergy GHGs	Increase in forest carbon sequestration (for organic materials)	Process and transportation emissions associated with recycling are counted in the manufacturing stage
Composting (food discards, yard trimmings)	NA	Increase in soil carbon storage	Compost machinery emissions and transportation emissions
Combustion	NA	NA	Nonbiogenic CO_2, N_2O emissions, avoided utility emissions, and transportation emissions
Landfilling	NA	NA	CH_4 emissions, long-term carbon storage, avoided utility emissions, and transportation emissions

NA = Not Applicable

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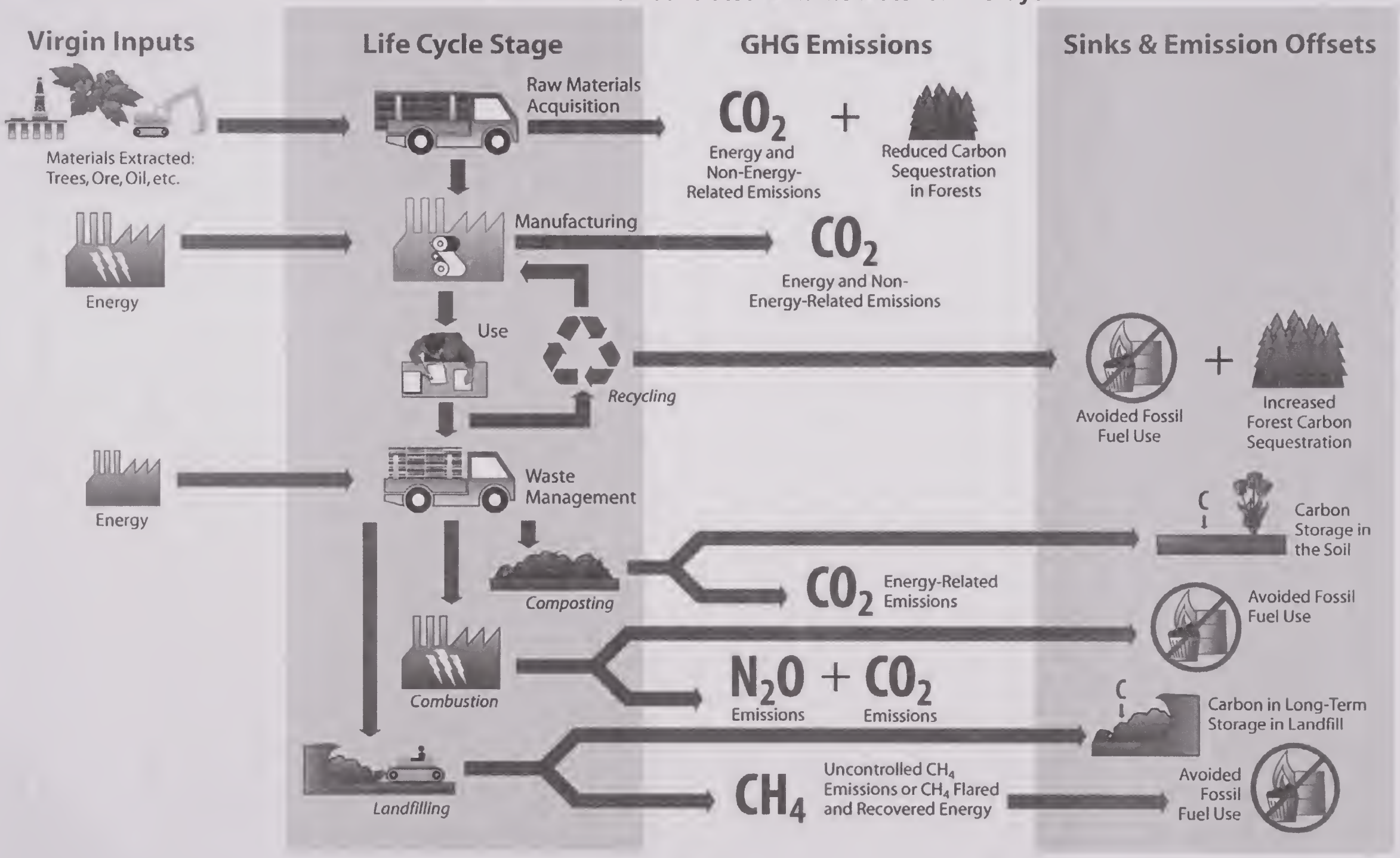
or reuse of a product. EPA did not analyze source reduction through material substitution (except in the special case of fly ash)—e.g., substituting plastic boxes for corrugated paper boxes. Nor did EPA estimate the potential for source reduction of chemical fertilizers and pesticides with increased production and use of compost. For a discussion of source reduction with material substitution, see Section 3.3.

Exhibit ES-3 Greenhouse Gas Sources and Sinks Associated with the Material Life Cycle



ES.6 RESULTS OF THE ANALYSIS

Management of municipal solid waste presents many opportunities for GHG emission reductions. Source reduction and recycling can reduce GHG emissions at the manufacturing stage, increase forest carbon sequestration, and avoid landfill CH_4 emissions. When waste is combusted, energy recovery displaces electricity generated by utilities by burning fossil fuels (thus reducing GHG emissions from the utility sector), and landfill CH_4 emissions are avoided. Landfill CH_4 emissions can be reduced by using gas recovery systems and by diverting organic materials from landfills. Landfill CH_4 can be flared or utilized for its energy potential. When used for its energy potential, landfill CH_4 displaces fossil fuels, as with MSW combustion.

In order to support a broad portfolio of climate change mitigation activities covering a range of GHGs, various methodologies for estimating emissions are needed. The primary result of this research is the development of material-specific GHG emission factors that can be used to account for the climate change benefits of waste management practices.

Exhibit ES-4 presents the GHG impacts of source reduction, recycling, composting, combustion, and landfilling. The impacts are calculated per short ton of waste managed. Please note that the emission factors presented in this report are intended to be compared with one another. They are not meant to reflect absolute values, but instead reflect the impact of choosing one waste management option over another for a given material type. This convention enabled EPA to calculate emission impacts from a waste generation reference point (i.e., from the moment a material is discarded). This process is in contrast to a typical life-cycle analysis, which reflects a raw materials extraction reference point. "Upstream" emissions and sinks are captured in EPA's streamlined methodology once a baseline waste management practice is compared to an alternative waste management practice.

In addition, this report does not include emissions from the use phase of a product's life, since use does not have an effect on the waste management emissions of a product. EPA took this approach because expert review of the first edition indicated that a waste management perspective would be more useful and comprehensible to waste managers, at whom this report is chiefly aimed.[27] The results are the same in the end, because it is the difference between the baseline and the alternative waste disposal scenarios that show the GHG savings from different treatment options; therefore, all tables and analyses in this report use a "waste generation" reference point. Exhibit ES-4 presents these values in MTCE/short ton of waste.[28] In these tables, emissions for 1 ton of a given material are presented across different management options. The life-cycle GHG emissions for each of the first four waste management strategies—source reduction, recycling, composting, and combustion—are compared to the GHG emissions from landfilling in Exhibit ES-5. These exhibits show the GHG values for each of the first four management strategies, minus the GHG values for landfilling. With these exhibits, one may compare the GHG emissions of changing management of 1 ton of each material from landfilling (often viewed as the baseline waste management strategy) to one of the other waste management options.

All values shown in Exhibit ES-4 and Exhibit ES-5 are for national average conditions (e.g., average fuel mix for raw material acquisition and manufacturing using recycled inputs; typical efficiency of a mass burn combustion unit; and national average landfill gas collection rates). GHG emissions are sensitive to some factors that vary on a local basis, and thus site-specific emissions will differ from those summarized here.

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[27] For the same results using a raw material extraction reference point, please see Appendix A.
[28] For the same results in $MTCO_2E$, please see Appendix B.

Following is a discussion of the principal GHG emissions and sinks for each waste management practice and the effect that they have on the emission factors:

- Source reduction, in general, represents an opportunity to reduce GHG emissions in a significant way. For many materials, the reduction in energy-related CO_2 emissions from the raw material acquisition and manufacturing process, and the absence of emissions from waste management, combine to reduce GHG emissions more than other options do.
- For most materials, recycling represents the second best opportunity to reduce GHG emissions. For these materials, recycling reduces energy-related CO_2 emissions in the manufacturing process (although not as dramatically as source reduction) and avoids emissions from waste management. Paper recycling increases the sequestration of forest carbon.
- Composting is a management option for food discards and yard trimmings. The net GHG emissions from composting are lower than landfilling for food discards (composting avoids CH_4 emissions), and higher than landfilling for yard trimmings (landfilling is credited with the carbon storage that results from incomplete decomposition of yard trimmings). Overall, given the uncertainty in the analysis, the emission factors for composting or combusting these materials are similar.
- The net GHG emissions from combustion of mixed MSW are lower than landfilling mixed MSW (under national average conditions for landfill gas recovery). Combustors and landfills manage a mixed waste stream; therefore, net emissions are determined more by technology factors (e.g., the efficiency of landfill gas collection systems and combustion energy conversion) than by material specificity. Material-specific emissions for landfills and combustors provide a basis for comparing these options with source reduction, recycling, and composting.

Exhibit ES-4
Net GHG Emissions from Source Reduction and MSW Management Options (MTCE/Ton)[a]

Material	Source Reduction[b]	Recycling	Composting	Combustion[c]	Landfilling[d]
Aluminum Cans	-2.24	-3.70	NA	0.02	0.01
Steel Cans	-0.87	-0.49	NA	-0.42	0.01
Copper Wire	-2.00	-1.34	NA	0.01	0.01
Glass	-0.16	-0.08	NA	0.01	0.01
HDPE	-0.49	-0.38	NA	0.25	0.01
LDPE	-0.62	-0.46	NA	0.25	0.01
PET	-0.57	-0.42	NA	0.30	0.01
Corrugated Cardboard	-1.52	-0.85	NA	-0.18	0.11
Magazines/Third-class Mail	-2.36	-0.84	NA	-0.13	-0.08
Newspaper	-1.33	-0.76	NA	-0.20	-0.24
Office Paper	-2.18	-0.78	NA	-0.17	0.53
Phonebooks	-1.72	-0.72	NA	-0.20	-0.24
Textbooks	-2.50	-0.85	NA	-0.17	0.53
Dimensional Lumber	-0.55	-0.67	NA	-0.21	-0.13
Medium-density Fiberboard	-0.60	-0.67	NA	-0.21	-0.13
Food Discards	NA	NA	-0.05	-0.05	0.20
Yard Trimmings	NA	NA	-0.05	-0.06	-0.06
Mixed Paper					
Broad Definition	NA	-0.96	NA	-0.18	0.09
Residential Definition	NA	-0.96	NA	-0.18	0.07
Office Paper Definition	NA	-0.93	NA	-0.16	0.13
Mixed Metals	NA	-1.43	NA	-0.29	0.01
Mixed Plastics	NA	-0.41	NA	0.27	0.01
Mixed Recyclables	NA	-0.79	NA	-0.17	0.04
Mixed Organics	NA	NA	-0.05	-0.05	0.06
Mixed MSW as Disposed	NA	NA	NA	-0.03	0.12
Carpet	-1.09	-1.96	NA	0.11	0.01
Personal Computers	-15.13	-0.62	NA	-0.05	0.01
Clay Bricks	-0.08	NA	NA	NA	0.01
Concrete	NA	0.00	NA	NA	0.01
Fly Ash	NA	-0.24	NA	NA	0.01
Tires	-1.09	-0.50[e]	NA	0.05	0.01

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[a] MTCE/ton: Metric tons of carbon equivalent per short ton of material. Material tonnages are on an as-managed (wet weight) basis.

[b] Source reduction assumes initial production using the current mix of virgin and recycled inputs.

[c] Values are for mass burn facilities with national average rate of ferrous recovery.

[d] Values reflect estimated national average CH_4 recovery in year 2003.

[e] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

Exhibit ES-5
GHG Emissions of MSW Management Options Compared to Landfilling (MTCE/Ton)[a]
(Management Option Net Emissions Minus Landfilling Net Emissions)

Material	Source Reduction[b] (Current Mix)	Source Reduction (100% Virgin Inputs)	Recycling	Composting[c]	Combustion[d]
Aluminum Cans	-2.26	-4.28	-3.71	NA	0.01
Steel Cans	-0.88	-1.02	-0.50	NA	-0.43
Copper Wire	-2.01	-2.03	-1.35	NA	0.00
Glass	-0.17	-0.19	-0.09	NA	0.00
HDPE	-0.50	-0.55	-0.39	NA	0.24
LDPE	-0.63	-0.65	-0.47	NA	0.24
PET	-0.58	-0.60	-0.43	NA	0.28
Corrugated Cardboard	-1.63	-2.32	-0.96	NA	-0.29
Magazines/Third-class Mail	-2.28	-2.36	-0.76	NA	-0.05
Newspaper	-1.09	-1.39	-0.52	NA	0.03
Office Paper	-2.71	-2.79	-1.31	NA	-0.70
Phonebooks	-1.49	-1.49	-0.49	NA	0.03
Textbooks	-3.03	-3.11	-1.38	NA	-0.70
Dimensional Lumber	-0.42	-0.42	-0.54	NA	-0.08
Medium-density Fiberboard	-0.47	-0.47	-0.54	NA	-0.08
Food Discards	NA	NA	NA	-0.25	-0.25
Yard Trimmings	NA	NA	NA	0.01	0.00
Mixed Paper					
Broad Definition	NA	NA	-1.06	NA	-0.27
Residential Definition	NA	NA	-1.03	NA	-0.25
Office Paper Definition	NA	NA	-1.06	NA	-0.29
Mixed Metals	NA	NA	-1.44	NA	-0.30
Mixed Plastics	NA	NA	-0.42	NA	0.26
Mixed Recyclables	NA	NA	-0.83	NA	-0.20
Mixed Organics	NA	NA	NA	-0.12	-0.12
Mixed MSW as Disposed	NA	NA	NA	NA	-0.15
Carpet	-1.10	-1.10	-1.97	NA	0.10
Personal Computers	-15.14	-15.14	-0.63	NA	-0.06
Clay Bricks	-0.09	-0.09	-0.01	NA	-0.01
Concrete	-0.01	-0.01	-0.01	NA	-0.01
Fly Ash	-0.01	-0.01	-0.25	NA	-0.01
Tires	-1.10	-1.10	-0.51[e]	NA	0.04

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[a] Values for landfilling reflect projected national average CH_4 recovery in year 2003.

[b] Source reduction assumes initial production using the current mix of virgin and recycled inputs.

[c] Calculation is based on assuming zero net emissions for composting.

[d] Values are for mass burn facilities with national average rate of ferrous recovery.

[e] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

The ordering of combustion, landfilling, and composting is affected by (1) the GHG inventory accounting methods, which do not count CO_2 emissions from sustainable biogenic sources,[29] but do count emissions from sources such as plastics; and (2) a series of assumptions on sequestration, future use of CH_4 recovery systems, system efficiency for landfill gas recovery, ferrous metal recovery, and avoided utility fossil fuels. On a site-specific basis, the ordering of results between a combustor and a landfill could be different from the ordering provided here, which is based on national average conditions.

EPA conducted sensitivity analyses to examine the GHG emissions from landfilling under varying assumptions about (1) the percentage of landfilled waste sent to landfills with gas recovery, and (2) CH_4 oxidation rate and gas collection system efficiency. The sensitivity analyses demonstrate that the results for landfills are very sensitive to these factors, which are site-specific.[30] Thus, using a national average value when making generalizations about emissions from landfills masks some of the variability that exists from site to site.

The scope of this report is limited to developing emission factors that can be used to evaluate GHG implications of solid waste decisions. EPA does not analyze policy options in this report. Nevertheless, the differences in emission factors across various waste management options are sufficiently large as to imply that GHG mitigation policies in the waste sector can make a significant contribution to U.S. emission reductions. A number of examples, using the emission factors in this report, illustrate this point.

- At the firm level, targeted recycling programs can reduce GHGs. For example, a commercial facility that shifts from (a) a baseline practice of landfilling (in a landfill with no gas collection system) 50 tons office paper and 4 tons of aluminum cans to (b) recycling the same materials can reduce GHG emissions by more than 100 MTCE.
- At the community level, a city of 100,000 with average waste generation (4.5 lbs/day per capita), recycling (30 percent), and baseline disposal in a landfill with no gas collection system could increase its recycling rate to 40 percent—for example, by implementing a pay-as-you-throw program—and reduce emissions by more than 3,400 MTCE per year. (Note that further growth in recycling would be possible; some communities already are exceeding recycling rates of 50 percent).
- A city of 1 million, disposing of 650,000 tons per year in a landfill without gas collection, could reduce its GHG emissions by about 260,000 MTCE per year by managing waste in a mass burn combustor unit.
- A town of 50,000 people landfilling a total of 30,000 tons per year could install a landfill gas recovery system with electricity generation and reduce emissions by about 13,500 MTCE per year.
- At the national level, if the United States attains the goal of a 35 percent recycling rate by 2008, emissions will be nearly 59 million MTCE per year lower than if no recycling took place.

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[29] Sustainable biogenic sources include paper and wood products from sustainably managed forests. When these materials are burned or aerobically decomposed to CO_2, the CO_2 emissions are not counted. The approach to measuring GHG emissions from biogenic sources is described in detail in Chapter 1.

[30] For details on the sensitivity analyses, see section 6.5 and Exhibits 6-7 and 6-8.

ES.7 OTHER LIFE-CYCLE GHG ANALYSES AND TOOLS

Life-cycle analysis is being used increasingly to quantify the GHG impacts of private and public sector decisions. In addition to the life-cycle analyses that underpin the emission factors in this report, Environmental Defense,[31] ICLEI, Ecobilan, and others have analyzed the life-cycle environmental impacts of various industry processes (e.g., manufacturing) and private and public sector practices (e.g., waste management). In many cases, the results of life-cycle analyses are packaged into software tools that distill the information according to a specific user's needs.

ICF International worked with EPA to create the WARM, ReCon, and DGC tools, in addition to researching and writing this report, and creating the emission factors used here and in the tools. As mentioned earlier, WARM was designed as a tool for waste managers to weigh the GHG and energy impacts of their waste management practices. As a result, the model focuses exclusively on waste sector GHG emissions, and the methodology used to estimate emissions is consistent with international and domestic GHG accounting guidelines. Life-cycle tools designed for broader audiences necessarily include other sectors and/or other environmental impacts, and are not necessarily tied to the Intergovernmental Panel on Climate Change (IPCC) guidelines for GHG accounting or the methods used in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.

- WARM is an EPA model that enables users to input several key variables (e.g., landfill gas collection system information, electric utility fuel mix, and transportation distances).[32] The model covers 34 types of materials and five waste management options: source reduction, recycling, combustion, composting, and landfilling. WARM accounts for upstream energy and nonenergy emissions, transportation distances to disposal and recycling facilities, carbon sequestration, and utility offsets that result from landfill gas collection and combustion. The tool provides participants in DOE's 1605(b) program with the option to report results by year, by gas, and by year and gas (although under 1605(b)'s revised guidelines, avoided emissions from recycling must be reported separately under "other indirect emissions" and not included in the main corporate inventory). WARM software is available free of charge in both a Web-based calculator format and a Microsoft® Excel spreadsheet. The tool is ideal for waste planners interested in tracking and reporting voluntary GHG emission reductions from waste management practices and for comparing the climate change impacts of different approaches. To access the tool, visit: http://www.epa.gov/mswclimate, then follow link to Tools.

- Recycled Content (ReCon) Tool was created by EPA to help companies and individuals estimate life-cycle GHG emissions and energy impacts from purchasing and/or manufacturing materials with varying degrees of postconsumer recycled content. The tool covers 17 material types and an analysis of baseline and alternative recycled-content scenarios. ReCon accounts for total "upstream" GHG emissions based on manufacturing processes, carbon sequestration, and avoided disposal that are related to the manufacture of the materials with recycled content. ReCon also accounts for the total energy (based on manufacturing processes and avoided disposal) related to the manufacture of materials with recycled content. The tool is ideal for companies and individuals who want to calculate GHG emissions and energy consumption associated with purchasing and manufacturing using baseline and alternate recycled-content scenarios. To access the tool, visit: http://www.epa.gov/mswclimate, then follow link to Tools.

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[31] Blum, L., Denison, R.A., and Ruston, V.F. 1997. A Life-Cycle Approach to Purchasing and Using Environmentally Preferable Paper: A Summary of the Paper Task Force Report," *Journal of Industrial Ecology*. I:3:15-46. Denison, R.A. 1996. "Environmental Life-Cycle Comparison of Recycling, Landfilling, and Incineration: A Review of Recent Studies"; *Annual Review of Energy and the Environment* 21:6:191-237.

[32] Microsoft Excel and Web-based versions of this tool are available online at the following website: http://www.epa.gov/globalwarming/actions/waste/tools.html.

- Durable Goods Calculator (DGC) is an EPA model that enables users to calculate the GHG emission and energy implications for various disposal methods of durable goods. The model covers 14 types of durable goods and three waste management options: recycling, landfilling, and combustion. The Durable Goods Calculator was developed for individuals and companies that want to make an informed decision on the GHG and energy impact of disposing of durable household goods. To access the tool, visit: http://www.epa.gov/mswclimate, then follow link to Tools.

- ICLEI Cities for Climate Protection (CCP) Campaign Greenhouse Gas Emission Software was developed by Torrie Smith Associates for ICLEI. This Windows™-based tool, targeted for use by local governments, can analyze emissions and emission reductions on a community-wide basis and for municipal operations alone. The community-wide module looks at residential, commercial, and industrial buildings; transportation activity; and community-generated waste. The municipal operations module looks at municipal buildings, municipal fleets, and waste from municipal in-house operations. In addition to computing GHG emissions, the CCP software estimates reductions in criteria air pollutants, changes in energy consumption, and financial costs and savings associated with energy use and other emission reduction initiatives. A version of the software program was made available for use by private businesses and institutions during the summer of 2001. CCP software subscriptions, including technical support, are available to governments participating in the program. For more information, visit: http://www.iclei.org/ or contact the U.S. ICLEI office at 510– 844–0699, iclei_usa@iclei.org.

- The MSW Decision Support Tool (DST) and life-cycle inventory database for North America have been developed through funding by ORD through a cooperative agreement with the Research Triangle Institute (CR823052). The methodology is based on a multimedia, multipollutant approach and includes analysis of GHG emissions as well as a broader set of emissions (air, water, and waste) associated with MSW operations. The MSW-DST is available for site-specific applications and has been used to conduct analyses in several states and 15 communities, including use by the U.S. Navy in the Pacific Northwest. The tool is intended for use by solid waste planners at state and local levels to analyze and compare alternative MSW management strategies with respect to cost, energy consumption, and environmental releases to the air, land, and water. The costs are based on full cost accounting principles and account for capital and operating costs using an engineering economics analysis. The MSW-DST calculates not only projected emissions of GHGs and criteria air pollutants, but also emissions of more than 30 air- and water-borne pollutants. The DST models emissions associated with all MSW management activities, including waste collection and transportation, transfer stations, materials recovery facilities, compost facilities, landfills, combustion and refuse-derived fuel facilities, utility offsets, material offsets, and source reduction. The differences in residential, multifamily, and commercial sectors can be evaluated individually. The software has optimization capabilities that enable one to identify options that evaluate minimum costs as well as solutions that can maximize environmental benefits, including energy conservation and GHG reductions.

  At the time of the publication of this report, the LCI database for North America was expected to be released in early- to mid-2006. The DST will be available on the Web. The MSW-DST provides extensive default data for the full range of MSW process models and requires minimum input data. However, these defaults can be tailored to the specific communities using site-specific information. The MSW-DST also includes a calculator for source reduction and carbon sequestration using a methodology that is consistent with the IPCC in terms of the treatment of biogenic CO_2 emissions. For more information, refer to the project website: http://www.rti.org/, then search the term "DST," or contact Keith Weitz, Research Triangle Institute, 919–541–6973, kaw@rti.org.

Comparison of EPA/ORD and EPA/OSW Emission Factors

An effort to harmonize previous life-cycle emission factors with the results of work by EPA's Office of Research and Development (ORD) was conducted in October 2000. Noticing significant differences in our bottom line emission factors, EPA compared a range of assumptions, including energy consumption, fuel mix, loss rates, landfill oxidation rate, timing of landfill methane emissions, fraction of landfill gas collected, electricity mix, transportation distances, and carbon storage. The comparison of energy intensities and fuel mixes included process and transportation energy for virgin and recycled production of each material type. Because the previous Office of Solid Waste (OSW) energy values were based on an average of Franklin Associates, Ltd. (FAL) and Tellus data, EPA compared the ORD values to the FAL data, Tellus data, and average of FAL and Tellus data.

This comparison revealed that the differences between the OSW and ORD emission factors are mostly attributable to the different assumptions about energy consumption (i.e., the sum of precombustion, process, and transportation energy), fuel mix, and loss rates. In general, it was found that ORD's total energy values are lower than OSW's energy values for both virgin and recycled materials. Comparing fuel mix, EPA found the most significant differences occurring for electricity, coal, natural gas, and "other" fuel types comprising process energy. The fractions of diesel fuel, residual fuel, and natural gas exhibited the greatest disparities for transportation energy. The comparison of loss rates, which are used to develop the recycling emission factors, showed significant variation for office paper, steel cans, and, to a lesser extent, newspaper.

In an effort to reconcile the remaining differences between ORD and OSW estimates of GHG emissions from the acquisition of raw materials and their manufacture into products, EPA identified additional methodological differences that could be affecting the recycling numbers. In particular, EPA found that ORD simulates closed-loop recycling for all materials, while OSW assumes open-loop recycling for office paper and corrugated cardboard. EPA also found that ORD's estimates do not include non-energy process emissions from perfluorocarbons (PFCs). To isolate any remaining differences between the two analyses, EPA substituted ORD energy intensities, fuel mixes, and loss rates into the OSW model.

Once all methodological differences between ORD and OSW estimates for raw materials acquisition and manufacturing had been identified and resolved, EPA selected the material types for which ORD data could be substituted for the existing OSW data: glass, HDPE, LDPE, PET, corrugated cardboard, magazines/third-class mail, newspaper, office paper, phonebooks, and textbooks. For wood products, ORD did not develop emission factors, while for steel its data was not sufficiently disaggregated to replace the existing OSW data.

- The Tool for Environmental Analysis and Management (TEAM), developed by Ecobilan, simulates operations associated with product design, processes, and activities associated with several industrial sectors. The model considers energy consumption, material consumption, transportation, waste management, and other factors in its evaluation of environmental impacts. For more information, visit: http://www.ecobalance.com/uk_team.php.

ES.8 LIMITATIONS OF THE ANALYSIS

When conducting this analysis, EPA used a number of analytical approaches and numerous data sources, each with its own limitations. In addition, EPA made and applied assumptions throughout the analysis. Although these limitations would be troublesome if used in the context of a regulatory framework, EPA believes that the results are sufficiently accurate to support their use in voluntary programs. Some of the major limitations include the following:

- The manufacturing GHG analysis is based on estimated industry averages for energy usage, and in some cases the estimates are based on limited data. In addition, EPA used values for the average GHG emissions per ton of material produced, not the marginal emission rates per incremental ton produced. In some cases, the marginal emission rates may be significantly different.

- The forest carbon sequestration analysis deals with a very complicated set of interrelated ecological and economic processes. Although the models used represent the state-of-the-art in forest resource planning, their geographic scope is limited. Because of the global market for forest products, the actual effects of paper recycling would occur not only in the United States but in Canada and other countries. Other important limitations include: (1) the model assumes that no forested lands will be converted to nonforest uses as a result of increased paper recycling; and (2) EPA uses a point estimate for forest carbon sequestration, whereas the system of models predicts changing net sequestration over time.
- The composting analysis considers a small sampling of feedstocks and a single compost application (i.e., agricultural soil). The analysis did not consider the full range of soil conservation and management practices that could be used in combination with compost and their impacts on carbon storage.
- The combustion analysis uses national average values for several parameters; variability from site to site is not reflected in the estimate.
- The landfill analysis (1) incorporates some uncertainty on CH_4 generation and carbon sequestration for each material type, due to limited data availability; and (2) uses estimated CH_4 recovery levels for the year 2003 as a baseline.

Finally, throughout most of the report, EPA expresses analytical inputs and outputs as point estimates. EPA recognizes that a rigorous treatment of uncertainty and variability would be useful, but in most cases the information needed to treat these in statistical terms is not available. The report includes some sensitivity analyses to illustrate the importance of selected parameters and expresses ranges for a few other factors such as GHG emissions from manufacturing. EPA encourages readers to provide more accurate information where it is available; perhaps with additional information, future versions of this report will be able to shed more light on uncertainty and variability. Meanwhile, EPA cautions that the emission factors reported here should be evaluated and applied with an appreciation for the limitations in the data and methods, as described at the end of each chapter.

1. LIFE-CYCLE METHODOLOGY

This report is the third edition of *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*. EPA made the following improvements to the second edition of the report:

- Developed emission factors for seven new material types: copper wire, clay bricks, concrete, fly ash, tires, carpet, and personal computers;
- Incorporated new energy data into calculations of electric utility offsets;
- Revised carbon coefficients and fuel use for national average electricity generation;
- Updated information on landfill gas recovery rates to reflect the latest values from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*;
- Added a discussion of emerging issues in the area of climate change and waste management;
- Provided a revised list of suggested proxy values for voluntary reporting of GHG emission reductions;
- Added a discussion of open-loop recycling, as it relates to emission factors for fly ash, carpet, personal computers, and mixed paper;
- Included emissions from retail transport in the methodology;
- Updated the current mix of postconsumer recycled content for various materials; and
- Updated the analysis of forest carbon sequestration and moved the discussion to the recycling chapter.

All of these changes and/or revisions are described in more detail throughout the body of the report.

In this edition of the report, EPA has moved some of the background information from the body of the report to separate background documents to improve clarity.[1] The technical details remain available to the interested, while keeping the main body of this report straightforward. *Background Document A: A Life Cycle of Process and Transportation Energy for Eight Different Materials* provides data on life-cycle energy intensity and fuel mix, provided by Franklin Associates, Ltd. (FAL). *Background Document B: Methodology for Estimating the Amounts and Types of Energy Consumed in Raw Materials Acquisition and Manufacturing of Eight Different Materials* provides a discussion of the review cycles leading up to the first and second editions of the report. *Background Document C: Review Process for the Report* includes a discussion of how the EPA researchers screened materials for the first edition of the report. *Background Document D: Comment-Response Document* presents comments and responses given during expert review of the first edition of the report. In addition to these four background documents, there are several material-specific background documents that explain how EPA developed specific emission factors for materials new to this edition of the report: copper wire, concrete, clay bricks, fly ash, tires, carpet, and personal computers.[2]

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[1] Available at EPA, Global Warming—Waste, "Solid Waste Management and Greenhouse Gases." Go to: http://www.epa.gov/mswclimate, then follow links to Publications → Reports, Papers, and Presentations → This report → Background Documents.

[2] These four background documents all have the same beginning to their titles: *Background Document for Life-Cycle Greenhouse Gas Emission Factors for* (1) *Clay Brick Reuse and Concrete Recycling*, (2) *Fly Ash Used as a*

The remainder of this chapter provides an overview of the methodology used to calculate the GHG emissions associated with various management strategies for MSW. The first section briefly describes the life-cycle framework used for the analysis. Next is a discussion of the materials included in the analysis. The final three sections present a description of key inputs and baselines, a summary of the life-cycle stages, and an explanation of how to estimate and compare net GHG emissions and sinks.

1.1 THE OVERALL FRAMEWORK: A STREAMLINED LIFE-CYCLE INVENTORY

Early in this analysis of the GHG benefits of specific waste management practices, it became clear that all waste management options provide opportunities for reducing GHG emissions, depending on individual circumstances. Although source reduction and recycling are often the most advantageous waste management practices from a GHG perspective, a material-specific comparison of all available waste management options clarifies where the greatest GHG benefits can be obtained for particular materials in MSW. A material-specific comparison can help waste managers and policymakers identify the best options for GHG reductions through alternative waste management practices.

This study determined that the best way to conduct such a comparative analysis is a streamlined application of a life-cycle assessment (LCA). A full LCA is an analytical framework for understanding the material inputs, energy inputs, and environmental releases associated with manufacturing, using, and disposing of a given material. A full LCA generally consists of four parts: (1) goal definition and scoping; (2) an inventory of the materials and energy used during all stages in the life of a product or process, and an inventory of environmental releases throughout the product life cycle; (3) an impact assessment that examines potential and actual human health effects related to the use of resources and environmental releases; and (4) an assessment of the change that is needed to bring about environmental improvements in the product or processes.

A full LCA is beyond the scope of this analysis. Rather, the streamlined LCA described in this report is limited to an inventory of the emissions and other environmental impacts related to global warming. This study did not assess human health impacts, necessary environmental improvements, and air, water, or environmental impacts that do not have a direct bearing on climate change. This analysis also simplifies the calculation of emissions from points in the life cycle that occur before a material is discarded. For a more extensive explanation of this "waste generation" reference point, see Section 1.5, below.

1.2 MSW MATERIALS CONSIDERED IN THE STREAMLINED LIFE-CYCLE INVENTORY

Each material in MSW has different GHG impacts depending on how it is manufactured and disposed of at the end of its useful life. EPA's research into these impacts began with a screening analysis of 37 of the most common materials and products found in MSW.[3] The materials included in screening analysis then were ranked by their potential for GHG reductions.[4] The second edition of the report

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Cement Replacement in Concrete, (3) *Carpet and Personal Computers*, and (4) *Copper Wire*. These are available at the EPA's Global Warming—Waste, "Solid Waste Management and Greenhouse Gases" website. Op cit.

[3] In addition to the materials and products covered in the report, the screening analysis included the following materials and products: other paper materials (bags and sacks, other paper packaging, books, other paperboard packaging, wrapping papers, paper plates and cups, folding cartons, other nonpackaging paper, and tissue paper and towels), other plastic materials (plastic wraps, plastic bags and sacks, other plastic containers, and other plastic packing), other metal materials (aluminum foil/closures, other steel packaging), and other miscellaneous materials (miscellaneous durable goods, wood packaging, furniture and furnishings, and other miscellaneous packaging).

[4] For more information on the screening analysis used to identify materials for the first edition of the report, see Background Document C, available at the EPA, Global Warming—Waste, "Background Documents for Solid Waste Management and GHG Report" website. Op cit.

included 16 materials: aluminum cans, steel cans,[5] glass, high-density polyethylene (HDPE) plastic blow-molded containers, low-density polyethylene (LDPE) plastic blow-molded containers, polyethylene terephthalate (PET) plastic blow-molded containers, corrugated cardboard, newspaper, office paper,[6] magazines and third-class mail, phonebooks, textbooks, dimensional lumber, medium-density fiberboard, food discards, and yard trimmings. In addition to these materials, EPA examined the GHG implications of various management strategies for, mixed MSW, mixed plastics, mixed organics, mixed recyclables, and three grades of mixed paper (broad, residential, and office). Most of the changes between the second and third editions of this report reflect additions of new or updated data. This third edition features a further expanded list of material types, including copper wire, clay bricks, concrete, fly ash, tires, and two composite materials: carpet and personal computers. Some of these new materials require a different approach than has been used in previous editions of the report. For more details on the methodology used to evaluate any of these new materials, please see the Background Documents.[7]

In this edition of the report, EPA has added emission factors for several new material types as described below:

- **Copper Wire**—copper wire was added to broaden the range of materials for which there are emission factors. Life-cycle data for copper wire were obtained in part from research on personal computers and their raw material inputs.
- **Clay Brick**—this material is analyzed for only two management options: source reduction (i.e. reuse of bricks) and landfilling. EPA research indicates that there is very little postconsumer recycling of bricks. Likewise, almost all bricks in this country are made from virgin materials, so EPA has not analyzed the impacts of using recycled material in brick manufacture.
- **Concrete**—in this context, concrete is recycled in a semiopen loop. EPA researchers analyzed concrete that is crushed and used in place of virgin aggregate (sand, gravel, etc.) in the manufacture of new concrete. It replaces virgin aggregate, not virgin concrete, although aggregate is used to create concrete.
- **Fly Ash**—as a byproduct of coal combustion, source reduction of fly ash is not considered to be a viable waste management option. Instead, EPA has modeled recycling of fly ash in an open loop for the purpose of displacing Portland cement in the production of concrete.
- **Tires**—tires were added as a material type due to the large number disposed in the United States every year. EPA has modeled the recycling of tires based on retreading and the combustion of tires based on their use as a tire-derived fuel (TDF).
- **Carpet**—carpet is a composite, meaning that recycling is necessarily more complicated than for single material products (like steel cans). For this analysis, EPA researchers considered only nylon broadloom residential carpet. Carpet consists of carpet fiber (nylon), carpet backing (usually polypropylene), and synthetic-latex-and-limestone adhesive. In this analysis, carpet is recycled only in an open-loop process, into carpet pad, carpet backing, and molded auto parts. Source reduction for carpet consists of making carpets thinner, or procedures to make replacement less frequent (e.g., cleaning and upkeep).

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[5] Other steel materials also may be recycled, but this analysis was limited to steel cans from households.

[6] Office paper refers to the type of paper used in computer printers and photocopiers.

[7] These are available at the EPA's Global Warming—Waste, "Solid Waste Management and Greenhouse Gases" website. Op cit.

- **Personal Computers**—PCs are also a composite and are a complex combination of many types of material; by weight the main components are plastics, glass, lead, steel, copper, and aluminum. PCs are recycled in an open-loop process; this report analyzes the production of asphalt, CRT (cathode ray tube) glass, lead bullion, steel sheet, copper wire, and aluminum sheet from recycled PCs. Source reduction of PCs includes finding ways to make PCs last longer.

This edition of the report also incorporates data developed by ORD through its work on life-cycle management of MSW. ORD's dataset on energy and fuel mix was thoroughly reviewed by industry and other stakeholders, and was more up-to-date than some of the information in the first edition of this report. Thus, where a complete set of energy intensity and fuel mix data was available from ORD, that information was incorporated into the second edition of this report. For other materials—steel cans and mixed paper (broad, residential, and office definitions)—EPA retained the original dataset developed by FAL. This edition includes data (also developed by FAL) on dimensional lumber and medium-density fiberboard. Exhibit 1-1 lists the materials that were analyzed for this report and the energy-related data sources underlying the estimates. All of the material types listed in Exhibit 1-1 are discussed in subsequent chapters and included in exhibits throughout the report, with the exception of three mixed waste categories. Mixed plastics, mixed recyclables, and mixed organics are included only in Chapter 7 because emission factors for these materials simply reflect the weighted average emissions of other material types.

Exhibit 1-1 Materials Analyzed and Energy-related Data Sources

Material	Energy Data Source	Material	Energy Data Source
Aluminum Cans	FAL	Clay Bricks	Athena[8]
Steel Cans	FAL	Concrete	USCB; USGS[9]
Copper Wire	FAL; Battelle[10]	Fly Ash	PCA[11]
Glass	ORD	Tires	CIEEDAC; AG[12]
Corrugated Cardboard	ORD	Carpet	FAL
Magazines/Third-class Mail	ORD	Personal Computers	FAL
Newspaper	ORD	Mixed Paper	
Office Paper	ORD	Broad Definition[13]	FAL
Phonebooks	ORD	Residential Definition	FAL
Textbooks	ORD	Office Paper Definition	FAL
Dimensional Lumber	FAL	Mixed Plastics	Weighted Average
Med.-density Fiberboard	FAL	Mixed Recyclables	Weighted Average
Food Discards	NA	Mixed Organics	NA
Yard Trimmings	NA	Mixed MSW	NA

NA = Not applicable (data not energy-related)

[8] Athena Sustainable Materials Institute, 1998, life-cycle research.

[9] U.S. Census Bureau, 1997 Economic Census; and Aggregates from Natural and Recycled Sources, a U.S. Geological Survey Circular by David Wilburn and Thomas Goonan.

[10] Battelle, 1975. Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing (Phase 4), Battelle Columbus Laboratories – U.S. Bureau of Mines. 1975.

[11] Portland Cement Association's (PCA) *U.S. Industry Fact Sheet, 2003 Edition*; the 2000 PCA report *Environmental Life Cycle Inventory of Portland Cement Concrete* by Nisbet, et al.; and the IPCC *Revised 1996 Guidelines for National Greenhouse Gas Inventories.*

[12] Canadian Industrial End-Use Energy Data and Analysis Center. Available online at: www.deh.gov.au/settlements/publications/waste/tyres/national-approach/; Atech Group, "A National Approach to Waste Tyres." Prepared for Environment Australia, June 2001. Available online at: www.deh.gov.au/settlements/publications/waste/tyres/national-approach/.

[13] For the composition of these three categories of mixed paper, please see Exhibit 3-2.

1.3 KEY INPUTS FOR THE STREAMLINED LIFE-CYCLE INVENTORY

Evaluating the GHG emissions of waste management requires analysis of three factors: (1) GHG emissions throughout the life cycle of the material (including the chosen disposal option); (2) the extent to which carbon sinks are affected by manufacturing and disposing of the material; and (3) the extent to which the management option recovers energy that can be used to replace electric utility energy, thus reducing utility GHG emissions.

GHG Emissions Relevant to Waste: The most important GHGs for purposes of analyzing MSW management options are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and perfluorocarbons (PFCs). Of these, CO_2 is by far the most common GHG emitted in the United States. Most CO_2 emissions result from energy use, particularly fossil fuel combustion. A great deal of energy is consumed when a product is manufactured and then discarded. This energy is used in the following stages: (1) extracting and processing raw materials; (2) manufacturing products; (3) managing products at the end of their useful lives; and (4) transporting materials and products from one life-cycle stage to another. This study estimated energy-related GHG emissions during all of these stages, except for transportation of products from retailers to consumers (because GHG emissions resulting from transportation to consumers will vary little among the options considered). Much of this report is devoted to explaining the methodology employed for quantifying the energy used—and the resulting CO_2 emissions—at each stage in the life cycle of any given material in MSW. Energy consumed in connection with consumer use of products is not evaluated, because it is assumed that energy use for the selected materials would be about the same whether the product is made from virgin or recycled inputs. In addition, energy use at this life-cycle stage is small (or zero) for all materials studied except personal computers.

CH_4, a more potent GHG, is produced when organic waste decomposes in an oxygen-free (anaerobic) environment, such as a landfill. CH_4 from landfills is the largest source of CH_4 in the United States;[14] these emissions are addressed in Chapter 6. CH_4 is also emitted when natural gas is released to the atmosphere during production of coal or oil, production or use of natural gas, and agricultural activities.

N_2O results from the use of commercial and organic fertilizers and fossil fuel combustion, as well as other sources. This analysis estimated N_2O emissions from waste combustion.

PFCs (tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6)) are emitted during the reduction of alumina to aluminum in the primary smelting process. The source of fluorine for CF_4 and C_2F_6 is the molten cryolite (Na_3AlF_6) where the reduction of alumina occurs. PFCs are formed when the fluorine in cryolite reacts with the carbon in the anode (a carbon mass of paste, coke briquettes,

Comparing GHGs

CO_2, CH_4, N_2O, and PFCs are very different gases in terms of their heat-trapping potential. An international protocol has established CO_2 as the reference gas for measurement of heat-trapping potential (also known as global warming potential or GWP). By definition, the GWP of 1kilogram (kg) of CO_2 is 1.

CH_4 has a GWP of 21, which means that 1 kg of CH_4 has the same heat-trapping potential as 21 kg of CO_2.

N_2O has a GWP of 310.

PFCs are the most potent GHG included in this analysis; GWPs are 6,500 for CF_4 and 9,200 for C_2F_6.

In this report, emissions of CO_2, CH_4, N_2O, and PFCs have been converted to their "carbon equivalents." Because CO_2 is 12/44 carbon by weight, 1 metric ton of CO_2 is equal to 12/44 or 0.27 metric tons of carbon equivalent (MTCE). The MTCE value for 1 metric ton of each of the other gases is determined by multiplying its GWP by a factor of 12/44. (All data provided here are from the IPCC, *Climate Change 1995: The Science of Climate Change*, 1996, p. 121.)

[14] EPA. 2005. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*. U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC. EPA-430-R-05-003.

or prebaked carbon blocks) and in the carbon lining that serves as the cathode. Although the quantities of PFCs emitted are small, these gases are significant because of their high global warming potential.

Carbon Stocks, Carbon Storage, and Carbon Sequestration: This analysis includes carbon storage to the extent that it is due to waste management practices. Carbon storage involves taking carbon-rich (biogenic) waste, such as wood products, and managing it so that the carbon is stored, rather than released to the atmosphere through burning or decay. For example, landfilled organic materials result in landfill carbon storage, as carbon is moved from a product pool (e.g., furniture) to the landfill pool. The same is true for composted organics that lead to carbon storage in soil.

Carbon sequestration differs from carbon storage because it represents a transfer of carbon from the atmosphere to a carbon pool, rather than the preservation of materials already containing carbon, as in landfilling. Carbon sequestration occurs when trees or other plants undergo photosynthesis, converting CO_2 in the atmosphere to carbon in their biomass. In this analysis, EPA considers the impact of waste management on forest carbon sequestration. The amount of carbon stored in forest trees is referred to as a forest's carbon stock.

The baseline against which changes in carbon stocks are measured is a projection by the U.S. Forest Service of forest growth, mortality, harvests, and other removals under anticipated market conditions for forest products. One of the assumptions for the projections is that U.S. forests will be harvested on a sustainable basis (i.e., trees will be grown at a rate at least equal to the rate at which they are cut).[15] Thus, the baseline assumes that harvesting trees at current levels results in no diminution of the forest carbon stock and no additional CO_2 in the atmosphere. On the other hand, forest carbon sequestration *increases* as a result of source reduction or recycling of paper products because both source reduction and recycling cause annual tree harvests to drop below otherwise anticipated levels (resulting in additional accumulation of carbon in forests). Consequently, source reduction and recycling "get credit" for increasing the forest carbon stock, whereas other waste management options (combustion and landfilling) do not.

Although source reduction and recycling are associated with forest carbon sequestration, composting—in particular, application of compost to degraded soils—enhances soil carbon storage. Four mechanisms of increased carbon storage are hypothesized in Chapter 4; a modeling approach is used to estimate the magnitude of carbon storage associated with three of those mechanisms.

Finally, landfills are another means by which carbon is removed from the atmosphere. Landfill carbon stocks increase over time because much of the organic matter placed in landfills does not decompose, especially if the landfill is located in an arid area. However, not all carbon in landfills is counted in determining the extent to which landfills are carbon stocks. For example, the analysis does not count plastic in landfills toward carbon storage. Plastic in a landfill represents simply a transfer from one carbon stock (the oil field containing the petroleum or natural gas from which the plastic was made) to another carbon stock (the landfill); thus, no change has occurred in the overall amount of carbon stored. On the other hand, the portion of organic matter (such as yard trimmings) that does not decompose in a landfill represents an addition to a carbon stock, because it would have largely decomposed into CO_2 if left to deteriorate on the ground.

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[15] Assuming a sustainable harvest in the United States is reasonable because from 1952 to 1997 U.S. forest carbon stocks steadily increased. In the early part of this period, the increases were mostly due to reversion of agricultural land to forest land. More recently, improved forest management practices and the regeneration of previously cleared forest areas have resulted in a net annual uptake (sequestration) of carbon. The steady increase in forest carbon stocks implies sustainable harvests, and it is reasonable to assume that the trend of sustainable harvests will continue.

Although changes in fossil fuel carbon stocks (i.e., reductions in oil field stores that result from the extraction and burning of oil resources) are not measured *directly* in this analysis, the reduction in fossil fuel carbon stocks is indirectly captured by counting the CO_2 emissions from fossil fuel combustion in calculating GHG emissions.

Avoided Electric Utility GHG Emissions Related to Waste: Waste that is used to generate electricity (either through waste combustion or recovery of CH_4 from landfills) displaces fossil fuels that utilities would otherwise use to produce electricity. Fossil fuel combustion is the single largest source of GHG emissions in the United States. When waste is substituted for fossil fuel to generate electricity, the GHG emissions from burning the waste are offset by the avoided electric utility GHG emissions. When gas generated from decomposing waste at a landfill is combusted for energy, GHG emissions are reduced from the landfill itself, and from avoided fossil fuel use for energy.

Reference Years: The reference year selected for most parts of the analysis is the most recent year for which data are available. However, for the system efficiency and ferrous recovery rate at waste combustors, this study uses values previously projected for the year 2000. For paper recycling, annual projections through 2019 were used to develop an average forest carbon storage value for the period from 2005 through 2019.[16] The compost analysis relied on model simulations of compost application, beginning in 1996 and ending in 2005. The carbon storage estimates resulting from these model runs correspond to model outputs in 2010. The EPA researchers developed "future"[17] scenarios for paper recycling, composting, and carbon storage analyses because some of the underlying factors that affect GHG emissions are changing rapidly, and this study seeks to define relationships (e.g., between tonnage of waste landfilled and CH_4 emissions) that represent an average over the next several years. Some of these scenarios are described in more detail below.

- When the first edition of this report was published in 1998, there were some small municipal waste combustors that did not recover energy. The modeling summarized in the report assumed that those facilities will be closed in the near future; all combustors are assumed to recover energy. The initial study also used an estimate provided by the combustion industry for anticipated levels of ferrous recovery.

- For paper recycling, earlier analyses indicated that the marginal impact of increased paper recycling on forest carbon sequestration changes over time. The impact also differs depending on the initial paper recycling rate and how that rate changes over time. To estimate the impact of increased paper recycling on forest carbon sequestration, the study needed to account for these influences. First, EPA used the American Forest and Paper Association's estimate of a 50 percent paper recycling rate in 2003.[18] The trajectory for a baseline scenario for paper recycling passes through 50 percent in 2000, with continued modest increases in the following years. Because of the need to estimate the impact of efforts (e.g., by EPA) to enhance recycling beyond the baseline projected rate, the researchers developed a plausible scenario for enhanced paper recycling rates and then compared the projected forest carbon sequestration under the baseline and increased recycling scenarios.[19] (This approach is fully described in Chapter 3.)

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[16] The models EPA used simulated carbon sequestration through 2040, but the researchers selected a value based on average conditions through 2020.

[17] In the case of system efficiency and ferrous recovery at waste combustors, the year 2000 represented a future value when the first edition of this report was published. The 2000 values have not been updated; therefore, the values in this report no longer reflect future conditions. This edition of the report does not reflect these updated values.

[18] Actual paper recovery in 2003 (taken from EPA's *Municipal Solid Waste in the United States: 2003 Facts and Figures*) averaged about 48 percent, confirming that 50 percent is a reasonable approximation for 2003.

[19] Note that this estimate is necessary for analyzing the scenarios; however, it does not represent a plan of action by EPA.

- The landfill recovery scenario is based on estimated recovery rates and percentages of waste disposed in landfills with no recovery, landfills with only flaring, and landfills with landfill-gas-to-energy projects for the year 2004. According to the researchers' estimates, 59 percent of all landfill CH_4 was generated at landfills with recovery systems, and the remaining 41 percent was generated at landfills without landfill gas (LFG) recovery.[20] Of the 59 percent of all CH_4 generated at landfills with LFG recovery, 53 percent (or 31 percent of all CH_4) was generated at landfills that use LFG to generate electricity, and 47 percent (or 28 percent of all CH_4) at landfills that flare LFG.[21]

1.4 SUMMARY OF THE LIFE-CYCLE STAGES

Exhibit 1-2 shows the GHG sources and carbon sinks associated with the manufacture of various materials and the postconsumer management of these materials as wastes. As shown in the exhibit, GHGs are emitted from (1) the preconsumer stages of raw materials acquisition and manufacturing, and (2) the postconsumer stage of waste management. No GHG emissions are attributed to the consumer's use of any product.

The remainder of this chapter describes how this study analyzed each of the upstream (raw materials acquisition, manufacturing, and forest carbon sequestration) and downstream (source reduction, recycling, composting, combustion, and landfilling) stages in the life cycle. The following sections explain stages of the life cycle (Exhibit 1-2) and the corresponding emission factor components (Exhibit 1-3), and outline the GHG emissions and carbon sinks associated with each stage. These GHG emissions and carbon sinks are described in detail and quantified for each material in Chapters 2 through 6.

1.4.1 GHG Emissions and Carbon Sinks Associated with Raw Materials Acquisition and Manufacturing

The top left corner of Exhibit 1-2 shows inputs for *raw materials acquisition*. These virgin inputs are used to make various materials, including ore for manufacturing metal products, trees for making paper products, and petroleum or natural gas for producing plastic products. Fuel energy also is used to obtain or extract these material inputs.

The inputs used in *manufacturing* are (1) energy and (2) either virgin raw materials or recycled materials. In the exhibit, these inputs are identified with arrows that point to the icon labeled "Manufacturing."

For source reduction, the "baseline" GHG emissions from raw materials acquisition and manufacturing are avoided. This analysis thus estimates, for source reduction, the GHG *reductions* (relative to a baseline of initial manufacture) at the raw materials acquisition and manufacturing stages. Source reduction is assumed to entail more efficient use of a given material. Examples are lightweighting (reducing the quantity of raw material in a product), double-sided photocopying, and extension of a product's useful life). In the case of clay bricks, source reduction refers to the reuse of old bricks. No other material substitutions are assumed for source reduction; therefore, this report does not

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[20] Based on landfill CH_4 generation and collection data from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004*), and an estimated national average landfill CH_4 recovery efficiency of 75 percent.

[21] The assumption that 53 percent of landfills recovering CH_4 use it to generate electricity is subject to change over time based upon changes in the cost of recovery, and the potential payback. Additionally, new technologies may arise that use recovered CH_4 for purposes other than generating electricity.

Exhibit 1-2 Greenhouse Gas Sources and Sinks Associated with the Material Life Cycle

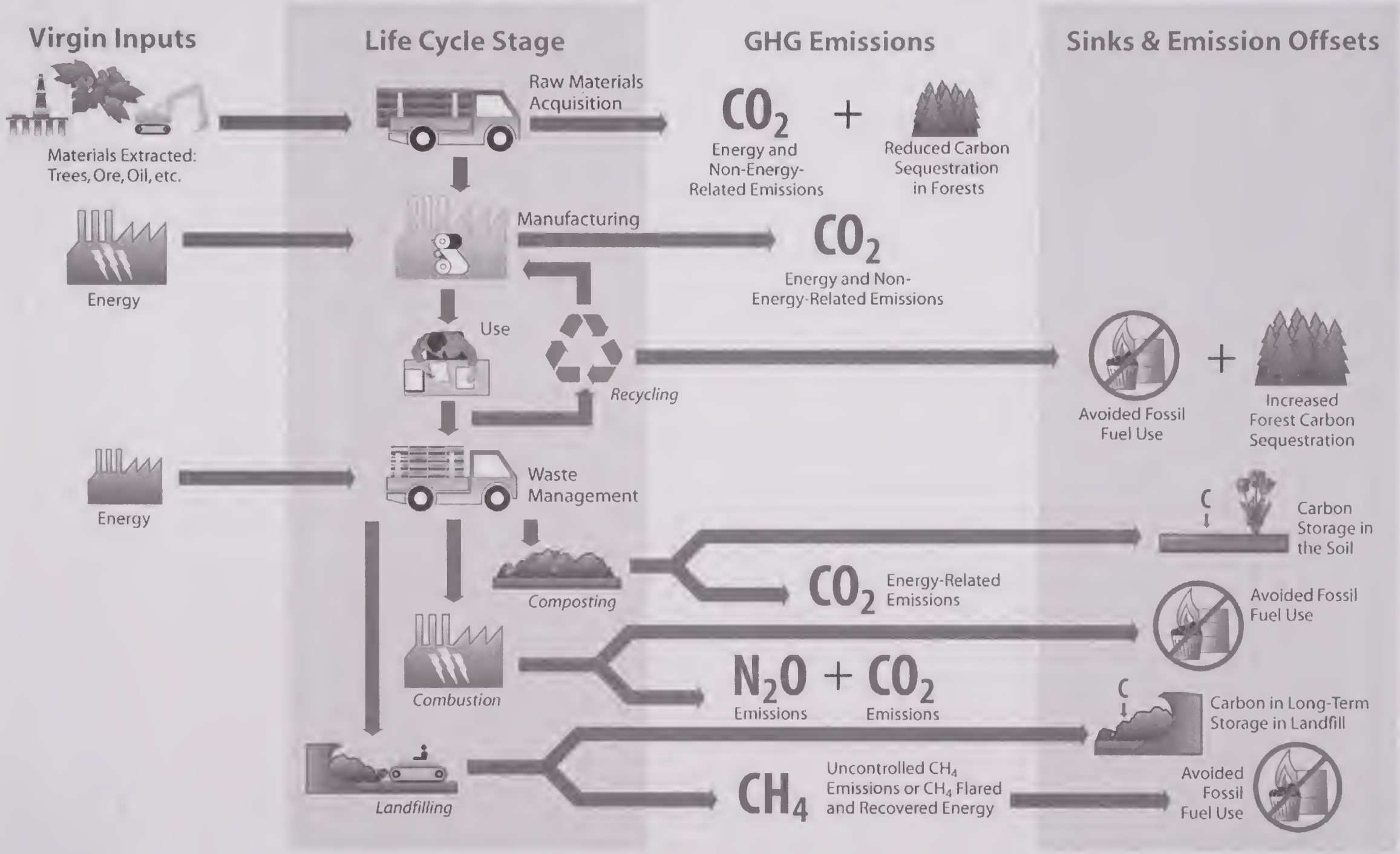

Exhibit 1-3 Components of Net Emissions for Various MSW Management Strategies

MSW Management Strategy	GHG Sources and Sinks		
	Process and Transportation GHGs from Raw Materials Acquisition and Manufacturing	Forest Carbon Sequestration or Soil Carbon Storage	Waste Management GHGs
Source Reduction	Decrease in GHG emissions, relative to the baseline of manufacturing	Increase in forest carbon sequestration	NA
Recycling	Decrease in GHG emissions due to lower energy requirements (compared to manufacture from virgin inputs) and avoided process nonenergy GHGs	Increase in forest carbon sequestration	Process and transportation emissions are counted in the manufacturing stage
Composting	No emissions/sinks[a]	Increase in soil carbon storage	Compost machinery emissions and transportation emissions
Combustion	Baseline process and transportation emissions due to manufacture from the current mix of virgin and recycled inputs	NA	Nonbiogenic CO_2, N_2O emissions, avoided utility emissions, and transportation emissions
Landfilling	Baseline process and transportation emissions due to manufacture from the current mix of virgin and recycled inputs	NA	CH_4 emissions, long-term carbon storage, avoided utility emissions, and transportation emissions

[a] No manufacturing transportation GHG emissions are considered for composting of food discards and yard trimmings because these materials are not considered to be manufactured.
NA = Not Applicable

analyze any corresponding increases in production and disposal of other materials (which could result in GHG emissions).[22] For some materials, such as fly ash, food discards, yard trimmings, and concrete, source reduction was not considered a possible management strategy.

The GHG emissions associated with raw materials acquisition and manufacturing are (1) GHG emissions from energy used during the acquisition and manufacturing processes, (2) GHG emissions from energy used to transport materials,[23] and (3) nonenergy GHG emissions resulting from manufacturing processes (for aluminum, steel, plastics, and office paper). Each type of emission is described below. Changes in carbon sequestration in forests also are associated with raw materials acquisition for paper products.

Process Energy GHG Emissions: Process energy GHG emissions consist primarily of CO_2 emissions from the combustion of fuels used in raw materials acquisition and manufacturing. CO_2 emissions from combustion of biomass are not counted as GHG emissions. (See "CO_2 Emissions from Biogenic Sources" text box.)

The majority of process energy CO_2 emissions are from the direct combustion of fuels, e.g., to operate ore mining equipment or to fuel a blast furnace. Fuel also is needed to extract the oil or mine the coal that is ultimately used to produce energy and transport those fuels to the place where they are used. Thus, indirect CO_2 emissions from this "precombustion energy" are counted in this category as well.

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[22] Although material substitution is not quantitatively addressed in the report, it is discussed from a methodological standpoint in Chapter 2 and also is discussed briefly in Chapter 3, Section 3.4.
[23] For some materials (plastics, magazines/third-class mail, office paper, phonebooks, and textbooks), the transportation data EPA received were included in the process energy data. For these materials, EPA reports *total* GHG emissions associated with process and transportation in the "process energy" estimate.

When electricity generated by combustion of fossil fuels is used in manufacturing, the CO_2 emissions from the fossil fuels also are counted.

To estimate process energy GHG emissions, the study first obtained estimates of both the total amount of process energy used per ton of product (measured in British thermal units or Btu), and the fuel mix (e.g., diesel oil, natural gas, fuel oil). Next, emissions factors for each type of fuel were used to convert fuel consumption to GHG emissions. As noted earlier, making a material from recycled inputs generally requires less process energy (and uses a different fuel mix) than making the material from virgin inputs.

The fuel mixes used in these calculations reflect the average U.S. fuel mixes for each manufacturing process. However, it is worth noting that U.S. consumer products (which eventually become MSW) increasingly come from overseas, where the fuel mixes may be different. For example, China relies heavily on coal and generally uses energy less efficiently than the United States. Consequently the GHG emissions associated with the manufacture of a material in China may be higher than for the same material made in this country. In addition, greater energy is likely to be expended on transportation to China than on transportation associated with domestic recycling. However, such analysis is beyond the scope of this report, which focuses only on domestic production, transportation, consumption, and disposal.

Details of the methodology for estimating process energy GHG emissions are provided in Chapter 2.

Transportation Energy GHG Emissions: Transportation energy GHG emissions consist of CO_2 emissions from the combustion of fuels used to transport raw materials and intermediate products to the retail/distribution point. The estimates of transportation energy emissions for transportation of raw materials to the manufacturing or fabrication facility are based on: (1) the amounts of raw material inputs and intermediate products used in manufacturing 1 ton of each material; (2) the average distance that each raw material input or intermediate product is transported; and (3) the transportation modes and fuels used. For the amounts of fuel used, the study used data on the average fuel consumption per ton-mile for each mode of transportation (this information can be found in Background Document A[24]). Then an emission factor for each type of fuel was used to convert the amount of each type of fuel consumed to the GHG emissions produced.

This edition includes estimates of GHG emissions from transporting manufactured products or materials from the manufacturing point to the retail/distribution point. The U.S. Census Bureau along with the Bureau of Transportation Statistics recently conducted a Commodity Flow Survey that determined the average distance commodities were shipped in the United States and the percentage each of the various transportation modes was used to ship these commodities.[25] However, there is large variability in the shipping distance and modes used, and so transportation emission estimates given here are somewhat uncertain. More detail on the methodology used to estimate transportation energy GHG emissions is provided in Chapter 2.

Process Nonenergy GHG Emissions: Some GHG emissions occur during the manufacture of certain materials and are not associated with energy consumption. In this analysis, these emissions are referred to as *process nonenergy emissions*. For example, the production of steel or aluminum requires lime (calcium oxide, or CaO), which is produced from limestone (calcium carbonate, or $CaCO_3$), and the manufacture of lime results in CO_2 emissions. Other process nonenergy GHG emissions are associated

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[24] *Background Document A: A Life Cycle of Process and Transportation Energy for Eight Different Materials.* Available at EPA's Global Warming—Waste, "Background Documents for Solid Waste Management and GHG Report" website. Op cit.

[25] U.S. Census Bureau, 2003. *Commodity Flow Survey.* United States Census Bureau. December, 2003. Available online at: http://www.census.gov/prod/ec02/02tcf-usp.pdf.

with the manufacture of plastics, office paper, and medium-density fiberboard. In some cases, process nonenergy GHG emissions are associated only with production using virgin inputs; in other cases, these emissions result when either virgin or recycled inputs are used. These emissions are described in Chapter 2.

Carbon Sinks: The only carbon sink associated with the raw materials acquisition and manufacturing stage is the additional carbon sequestration in trees associated with source reduction or recycling of paper products. The methodology for estimating forest carbon sequestration is described in Chapter 3.

1.4.2 GHG Emissions and Carbon Sinks Associated with Waste Management

As shown in Exhibit 1-3, there are up to five postconsumer waste management options, depending on the material: source reduction, recycling, composting, combustion, and landfilling. This section describes the GHG emissions and carbon sinks associated with each option.

Source Reduction: In this analysis, source reduction is measured by the amount of material that would otherwise be produced but is not generated due to a program promoting source reduction. The avoided GHG emissions are based on raw material acquisition and manufacturing processes for the average current mix of virgin and recycled inputs for materials in the marketplace.[26] There are no emissions from MSW management.

Recycling: When a material is recycled, it is used in place of virgin inputs in the manufacturing process. The avoided GHG emissions from remanufacture using recycled inputs is calculated as the difference between (1) the GHG emissions from manufacturing a material from 100 percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the material (accounting for loss rates) from 100 percent virgin inputs (including the process of collecting and transporting the recyclables). No GHG emissions occur at the MSW management stage because the recycled material is diverted from waste management facilities.[27] (If the product made from the recycled material is later composted, combusted, or landfilled, the GHG emissions at that point would be attributed to the product that was made from the recycled material.) Chapter 3 details GHG emissions from recycling.

Materials are recycled either in "closed-loop" or "open-loop" processes. Closed loop means that a product is recycled into the same product; an example is an aluminum can recycled into another aluminum can. Open loop means that the secondary product is different than the primary product and often occurs when a material is degraded or changed by the recycling process. Most of the materials considered in this analysis are modeled as being recycled in a closed loop. However, a variety of paper types are recycled under the general heading of "mixed paper." Mixed paper can be remanufactured, via an open loop, into boxboard or paper towels. Other materials are recycled in open-loop processes, but due to limited resources, this study could not analyze all open-loop processes.[28] Three newly added materials, fly ash, carpet, and PCs, are analyzed only in an open-loop process. In the case of PCs, the used computers are sent to a processing facility where various components, such as copper, lead, glass, and plastic, are put into separate streams. Carpet is also remanufactured into secondary materials other than carpet.

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[26] Changes in the mix of production (i.e., higher proportions of either virgin or recycled inputs) result in incremental emissions (or reductions) with respect to this reference point.

[27] The EPA researchers did not include GHG emissions from managing residues (e.g., wastewater treatment sludges) from the manufacturing process for either virgin or recycled inputs.

[28] For example, not all steel cans are recycled into more steel cans; not all aluminum cans are recycled into more aluminum cans, but for the purposes of this report, EPA assumes they are.

CO_2 Emissions from Biogenic Sources

The United States and all other parties to the UNFCCC agreed to develop inventories of GHG emissions as part of its stated goals of stabilizing emissions and preventing dangerous anthropogenic climate change. The IPCC developed a set of inventory methods to be used as the international standard. (IPCC 1997. *IPCC Guidelines for National Greenhouse Gas Inventories*, three volumes.) The methodologies used in this report to evaluate emissions and sinks of GHGs are consistent with the IPCC guidance.

One of the elements of the IPCC guidance that deserves special mention is the approach used to address CO_2 emissions from biogenic sources. For many countries, the treatment of CO_2 releases from biogenic sources is most important when addressing releases from energy derived from biomass (e.g., burning wood), but this element is also important when evaluating waste management emissions (for example, the decomposition or combustion of grass clippings or paper). The carbon in paper and grass trimmings was originally removed from the atmosphere by photosynthesis, and under natural conditions, it would cycle back to the atmosphere eventually as CO_2 due to degradation processes. The quantity of carbon that these natural processes cycle through the Earth's atmosphere, waters, soils, and biota is much greater than the quantity added by anthropogenic GHG sources. But the focus of the UNFCCC is on anthropogenic emissions—those resulting from human activities and subject to human control. Those emissions have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle and altering the atmosphere's heat-trapping ability. For processes with CO_2 emissions, if the emissions are from biogenic materials and the materials are grown on a sustainable basis, then those emissions are considered simply to close the loop in the natural carbon cycle. They return to the atmosphere CO_2 that was originally removed by photosynthesis. In this case, the CO_2 emissions are the CO_2 emissions are not anthropogenic and therefore *not* included in emission inventories. (For purposes of this analysis, biogenic materials are paper, yard trimmings, and food discards.) On the other hand, CO_2 emissions from burning fossil fuels *are* counted because these emissions would not enter the cycle were it not for human activity. Likewise, CH_4 emissions from landfills *are* counted. Even though the source of carbon is primarily biogenic, CH_4 would not be emitted were it not for the human activity of landfilling the waste, which creates anaerobic conditions conducive to CH_4 formation. Note that this approach does not distinguish between the timing of CO_2 emissions, provided that they occur in a reasonably short time scale relative to the speed of the processes that affect global climate change. In other words, as long as the biogenic carbon would eventually be released as CO_2, whether it is released virtually instantaneously (e.g., from combustion) or over a period of a few decades (e.g., decomposition on the forest floor), it is treated the same.

Composting: When organic materials are composted, the anaerobic decomposition of materials produces CH_4. Similarly, the collection and transportation of organics produces nonbiogenic emissions. During the composting process and after the compost is added to the soil, the decomposition of plants produces biogenic CO_2 emissions. All of the materials that may be composted (e.g., leaves, brush, grass, food waste, newspaper) originally are produced by trees or other plants. As described in the above "CO_2 Emissions from Biogenic Sources," the biogenic CO_2 emitted from these materials during composting is not counted toward GHG emissions. However, composting does result in increased soil carbon storage due to increased production of humic material (natural organic polymers, which degrade at a slow rate) and several other factors, which are described in Chapter 4.

Although composting may result in some production of CH_4 (due to anaerobic decomposition in the center of the compost pile), compost researchers believe that the CH_4 almost always oxidizes to CO_2 before it escapes from the compost pile.

Because the CO_2 emissions from composting are biogenic, and well-managed compost piles are not believed to produce CH_4, the only GHG emissions from composting result from transportation of compostable materials to composting facilities and mechanical turning of the compost piles. GHG emissions associated with compost application are discussed in Chapter 4.

Combustion: When waste is combusted, two GHGs are emitted: CO_2 and N_2O. Nonbiogenic CO_2 emitted during combustion (i.e., CO_2 from plastics) is counted toward the GHG emissions associated with combustion, but biogenic CO_2 is not. Because most waste combustors produce electricity that substitutes for utility-generated electricity, the net GHG emissions are calculated by subtracting the utility GHG emissions avoided from the gross GHG emissions. GHG emissions from combustion are described in Chapter 5.

Landfilling: When organic matter is landfilled, some of this matter decomposes anaerobically and releases CH_4, a GHG. Some of the organic matter never decomposes at all; instead, the carbon becomes stored in the landfill. (Landfilling of metals and plastics does not result in CH_4 emissions or carbon storage.)

At some landfills, virtually all of the CH_4 produced is released to the atmosphere. At others, CH_4 is captured for flaring or combustion with energy recovery (e.g., electricity production). Almost all of the captured CH_4 is converted to CO_2, but that CO_2 is not counted in this study as a GHG because it is biogenic. With combustion of CH_4 for energy recovery, emission factors reflect the electric utility GHG emissions avoided. Regardless of the fate of the CH_4, the landfill carbon storage associated with landfilling of some organic materials is accounted for. GHG emissions and carbon sinks from landfilling are described in Chapter 6.

1.5 ESTIMATING AND COMPARING NET GHG EMISSIONS

To calculate the net GHG implications of a waste management strategy for a given material, baseline and alternative scenarios must be established. For example, a baseline scenario in which 10 tons of office paper are manufactured, used, and landfilled could be compared with an alternative scenario in which 10 tons are manufactured, used, and recycled. For this example, net GHG emissions are calculated as the difference between landfilling emissions and the emissions/emission reductions associated with recycling. The general formula for net GHG emissions for each scenario is as follows:

Net GHG emissions = Gross manufacturing GHG emissions - (Increase in carbon stocks + Avoided utility GHG emissions)

Comparing net GHG emissions for the two scenarios enables the lowest net GHG emissions to be identified. The following circumstances influence the net GHG emissions of a material:

- Through *source reduction* (for example, "lightweighting" a beverage can—using less aluminum for the same function), GHG emissions throughout the life cycle are avoided. In addition, when paper products are source reduced, additional carbon is sequestered in forests, through reduced tree harvesting.
- Through *recycling*, the GHG emissions from making an equivalent amount of material from virgin inputs are avoided. In most cases, recycling reduces GHG emissions because manufacturing a product from recycled inputs requires less energy than making the product from virgin inputs.
- *Composting* results in carbon sequestration of organic materials.
- *Landfilling* results in CH_4 emissions. If captured, the CH_4 may be flared, which simply reduces CH_4 emissions (since the CO_2 produced by flaring is biogenic in origin, it is not accounted for in this assessment of anthropogenic emissions). If captured CH_4 is burned to produce energy, it offsets emissions from fossil fuel consumption.
- *Combustion* of waste may result in an emissions offset if the waste is burned in a waste-to-energy facility, which displaces fossil-fuel derived electricity.

In calculating emissions for the life-cycle scenarios, one can utilize a "raw material extraction" reference point, or a "waste generation" reference point. The raw material extraction reference point is a cradle-to-grave approach, in which emissions are calculated starting with the extraction of raw materials (e.g., ore) used to create virgin inputs. Since this report is designed to be used mainly by solid waste managers, the emission factors presented in the main body of the document are based on the waste generation reference point, one that starts when a material is discarded. Emission factors using a raw material extraction reference point are presented in the Appendices.

Exhibit 1-3 indicates how GHG sources and sinks have been counted for each MSW management strategy in order to estimate net GHG emissions using the postconsumer waste generation reference point. For example, the top row of the exhibit shows that source reduction (1) reduces GHG emissions from raw materials acquisition and manufacturing, (2) results in an increase in forest carbon sequestration, and (3) does not result in GHG emissions from waste management. The sum of emissions (and sinks) across all steps in the life cycle represents net emissions. Section 7.2, "Accounting for Emission Reductions and Energy Savings," describes how waste managers and companies have used these emission factors to estimate GHG emissions and potential GHG emission reductions associated with integrated waste management. In addition, EPA uses these emission factors to develop WARM, which enables users to analyze the GHG savings associated with changing their waste management practices. EPA also recently developed the ReCon Tool and the Durable Goods Calculator (DGC). The ReCon tool helps both individual and corporate consumers calculate the GHG and energy benefits of purchasing or manufacturing materials with varying recycled content; the DGC allows consumers to calculate the GHG and energy impacts of different disposal methods for durable goods such as refrigerators and televisions. As with WARM, the ReCon Tool is available as both an online calculator and as a spreadsheet tool, while the DGC is currently available only as a spreadsheet tool.[29]

[29] Available at the EPA, Global Warming—Waste website. Op cit. WARM and ReCon are available at: http://www.epa.gov/mswclimate, then follow link to Tools.

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2. RAW MATERIALS ACQUISITION AND MANUFACTURING

The GHG emissions associated with raw materials acquisition and manufacturing are a key element of a life-cycle GHG analysis. This chapter describes how EPA estimated these emissions for 21 materials: aluminum cans, steel cans, copper wire, glass, three types of plastic (HDPE, LDPE, and PET), corrugated cardboard, magazines/third-class mail, newspaper, office paper, phonebooks, textbooks, dimensional lumber, medium-density fiberboard, carpet, personal computers, clay bricks, concrete, fly ash, and tires. This chapter also includes a similar analysis for three definitions of mixed paper (broad, residential, and office).

In manufacturing, substantial amounts of energy are used both in the acquisition of raw materials and in the manufacturing process itself. In general, the majority of energy used for these activities is derived from fossil fuels. Combustion of fossil fuels results in emissions of CO_2, a GHG. In addition, manufacturing of some materials also results in GHG emissions that are not associated with energy consumption. Section 2.1 addresses energy-related CO_2 emissions, and Section 2.2 covers nonenergy GHG emissions. Sections 2.3 and 2.4 discuss results and limitations of the analysis, respectively.

2.1 GHG EMISSIONS FROM ENERGY USE IN RAW MATERIALS ACQUISITION AND MANUFACTURING

To begin this analysis, EPA estimated the GHG emissions from fossil fuel combustion for both (1) raw materials acquisition and manufacturing (referred to here as "process energy"), and (2) transportation (referred to as "transportation energy").

In this analysis, process energy GHG emissions consist primarily of CO_2.[1] The majority of CO_2 emissions are from combustion of fuels used directly, e.g., to operate mining equipment or fuel a blast furnace. CO_2 emissions from fuels used to generate electricity during the manufacturing stage also are included in process energy emissions. In addition, process energy GHG emissions include indirect emissions from "precombustion" activities, such as oil exploration and extraction, coal mining and beneficiation, and natural gas production.

Transportation energy GHG emissions consist of CO_2 emissions from combustion of fuels used to transport raw materials and intermediate products to the final manufacturing or fabrication facility. For transportation of recycled inputs, this analysis considers transportation (1) from the curbside to the materials recovery facility (MRF), (2) from the MRF to a broker, and (3) from a broker to the plant or mill where the recycled inputs are used. The transportation values for recycled inputs generally include the energy used to process the inputs at a MRF. Transportation of finished manufactured goods to consumers is not included in the analysis; however, this edition of the report does include transportation emissions from the manufacturer to the retailer. EPA did not estimate transportation emissions of CH_4 or N_2O; these emissions are considerably less significant than CO_2 emissions from transportation activities.[2] This omission would tend to understate the GHG impacts from transportation slightly.

Emissions from raw materials acquisition and manufacturing also include CH_4 associated with producing, processing, and transporting coal, oil, and natural gas. CH_4 is emitted during the various stages of fossil fuel production because CH_4 is trapped within coal and oil deposits, and is released when they are mined. Natural gas, of course, consists largely of CH_4.

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[1] Note, however, that CO_2 emissions from combustion of biomass (e.g., in paper manufacturing) are not counted as GHG emissions (as described in Chapter 1).

[2] The *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004* estimates 2004 emissions from transportation to be 506.0 MMTCE for CO_2 and 12.1 MMTCE for CH_4 and N_2O combined.

EPA developed separate estimates for GHG emissions from process and transportation energy for virgin inputs and recycled inputs, generating a total of four separate GHG emission estimates for each material: (1) process energy with virgin inputs, (2) process energy with recycled inputs, (3) transportation energy for materials made from virgin inputs, and (4) transportation energy for materials made from recycled inputs.

2.1.1 Methodology

Virgin and recycled emission estimates for material processing and transportation were developed using two sets of data: (1) the amount of each type of fuel consumed per ton of the material, and (2) the "carbon coefficient" for each fuel (a factor that translates the energy value of fuel combusted into the mass of GHGs emitted).

EPA's methodology in using these two sets of data to estimate process and transportation energy GHG emissions is best illustrated by an example. To estimate process energy GHG emissions from the production of 1 ton of steel from virgin inputs, the EPA researchers multiplied the amount of each type of fuel consumed (as measured in million Btu) by the carbon coefficient for that type of fuel (as measured in metric tons of carbon equivalent, or MTCE, per million Btu). The result was an estimate of the GHG emissions (in MTCE) from the combustion of each type of fuel required to make 1 ton of steel. Total process energy GHG emissions from making 1 ton of steel are simply the sum of the GHG emissions across all of the fuel types. To estimate the GHG emissions when electricity is used, EPA used the national average mix of fuels used to generate electricity.

EPA estimated GHGs from the energy used to transport raw materials necessary for 1 ton of a given product (e.g., steel) to the retailer, and the energy used to transport the product from the manufacturer to the retail point, in the same way. The amount of each fuel used was multiplied by its carbon coefficient, and the resulting values for each of the fuels were summed to yield total transportation energy GHG emissions.

In this way, GHG estimates for raw materials acquisition and manufacturing were developed for each of the manufactured materials considered. As noted in Chapter 1, much of the energy information reflected in the analysis is drawn from an effort conducted by EPA's ORD to construct a Decision Support Tool for solid waste managers. The remaining energy data were developed by FAL as part of the original effort or subsequent updates.

Most of the materials included in this analysis are assumed to undergo closed-loop recycling (i.e., primary material type is remanufactured into the same material type). However, several materials are recycled in an open loop, where the primary material type is remanufactured into a different secondary material; these materials are mixed paper, corrugated cardboard, fly ash, carpet, and personal computers. The exhibits in this chapter show data not only for the 21 primary materials of interest, but also for secondary materials such as boxboard, carpet pad, carpet backing, molded auto parts, asphalt, CRT glass, lead bullion, and copper wire. Because recycling processes data are similar for HDPE, LDPE, and PET, EPA adopted the approach used by ORD of using a single energy profile (fuel mix and energy intensity) for all recycled plastics. For steel cans, EPA developed the GHG estimates for virgin production using the basic oxygen furnace process, and for recycled production, electric arc furnace process was used.[3]

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[3] Two types of furnace are used in recycling steel: electric arc (EAF), which uses nearly 100 percent recovered inputs, and basic oxygen (BOF), which uses 25 to 35 percent recovered steel. Steel from EAFs is structurally unsuited to milling into thin sheets to make steel cans. Therefore, although EPA models steel can recycling as a closed-loop process (steel cans made into steel cans), this is not entirely accurate, statistically. By modeling recovery of steel cans as a closed-loop process, EPA implicitly assumed that 1 ton of steel produced from recovered steel cans in an electric arc furnace displaces 1 ton of steel produced from virgin inputs in a basic oxygen furnace. However, the EPA researchers feel that the values from the two furnaces are close enough to make closed-loop

Carbon coefficients from DOE's Energy Information Administration for all energy sources except electricity were used.[4] The carbon coefficient for electricity was based on the weighted average carbon coefficients for all fuels used to generate electricity in the United States.[5]

Because the carbon coefficients from these sources only account for the CO_2 emissions from combustion of each type of fuel, EPA added to these carbon coefficients (1) the average amount of CH_4 emitted during the production, processing, and transportation of fossil fuels, and (2) the average CO_2 emissions from oil production, due to the flaring of natural gas. EPA calculated the average fugitive GHG emissions associated with U.S. production of coal, oil, and natural gas. The resulting average estimates for fugitive GHG emissions from fossil fuel production were 0.92 kg of carbon equivalent per million Btu (kg CE/million Btu) for coal, 0.10 kg CE/million Btu for oil, and 0.70 kg CE/million Btu for natural gas.[6]

The carbon coefficients that reflect both CO_2 and CH_4 emissions are supplied in Exhibit 2-1. (All exhibits are provided at the end of this chapter.)

The fuel mixes used in these calculations reflect the average U.S. fuel mixes for each process. However, it is worth noting that U.S. consumer products (which eventually become MSW) increasingly come from overseas, where the fuel mixes may be different. For example, China relies heavily on coal and generally uses energy less efficiently than the United States. Consequently the GHG emissions associated with the manufacture of a given product in China may be higher than for the same product made in this country. However, such analysis is beyond the scope of this report, which focuses only on domestic production, transportation, consumption, and disposal.

The process and transportation GHG values are summarized in Exhibit 2-2. For each product and each type of input (virgin or recycled), EPA summed the estimates for process and transportation GHG emissions, as shown in columns "b" (for virgin inputs) and "c" (for recycled inputs) of Exhibit 2-2. EPA also estimated the energy-related GHG emissions from manufacturing each material from the current mix of virgin and recycled inputs.[7] These values are shown in column "e." (The remaining two columns of Exhibit 2-2 are discussed later in this chapter.)

The energy intensity and fuel mix data are provided in Exhibit 2-3 through Exhibit 2-6. For most materials, the data in the exhibits are for manufacturing processes that either use (1) 100 percent virgin inputs or (2) 100 percent recycled inputs.[8]

To estimate the types and amounts of fuels used for process and transportation energy, ORD and FAL relied on published data (such as engineering handbooks and published production data), contacts

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recycling a reasonable assumption. (For the fabrication energy required to make steel cans from steel, EPA used the values for fabrication of steel cans from steel produced in a basic oxygen furnace.)

[4] DOE, Energy Information Administration. 2004. *Annual Energy Review: 2003.*

[5] FAL reported the Btu value for electricity in terms of the Btu of fuel combusted to generate the electricity used at the factory, rather than the (much lower) Btu value of the electricity that is delivered to the manufacturer. Thus, FAL had already accounted for the efficiency of converting fuels to electricity, and the losses in transmission and distribution of electricity. EPA therefore did not need to account for these factors in the carbon coefficient for electricity.

[6] ICF Consulting. 1995. Memorandum, "Fugitive Methane Emissions from Production of Coal, Natural Gas, and Oil," August 8, updated to use global warming potential for CH_4 of 21.

[7] The current mix of virgin and recycled inputs is derived from FAL data, and varies from material to material.

[8] In the FAL data set, the one exception is the data for steel cans made from virgin inputs, for which FAL provided data for manufacture from 80 percent virgin inputs and 20 percent recycled inputs. EPA (or ICF Consulting) extrapolated from this data (and the corresponding values for production using 100 percent recycled inputs) to obtain estimates of the energy inputs for manufacturing these materials from 100 percent virgin inputs. Similarly, for corrugated cardboard, ORD assumed that a virgin corrugated box contains a minimum of 14.7 percent total recycled content.

with industry experts, and review by stakeholders and trade organizations. ORD and FAL counted all energy, no matter where it was used. For example, much aluminum produced in the United States is made from bauxite that is mined and processed into alumina in other countries. The energy required for overseas bauxite mining and processing is included in the analysis.

The EPA methodology also accounts for GHG emissions associated with the transport of materials as commodities (i.e., manufactured products or materials) from the manufacturing point to the retail/distribution point. The U.S. Census Bureau along with the Bureau of Transportation Statistics recently conducted a Commodity Flow Survey that determined the average distance commodities were shipped in the United States and the percentage each of the various transportation modes was used in shipping these commodities.[9] The estimated transportation energy for each material type was estimated by applying the transportation fuel efficiency and fuel-specific heating value to the average miles that commodities were shipped within each mode. Although these factors may be small relative to the larger raw materials acquisition and manufacturing emissions for each material, their inclusion adds to the robustness of the life-cycle methodology. Because this adjustment was made to both the 100 percent virgin and 100 percent recycled material types, the change in transportation emissions will drop out when virgin and recycled materials are compared. Because source reduction emission factors reflect the benefit of not transporting the material in the first place, the adjustment will be more noticeable. For additional details on the methodology for estimating retail transportation for materials please see the *WARM Retail Transportation* background document.[10]

Finally, it should be noted that during EPA's extensive review of ORD and FAL data, the most critical assumptions and data elements that each model used were examined to ensure that they accurately reflect the energy requirements of the raw materials acquisition and manufacturing for the material types considered. Nevertheless, EPA recognizes that different manufacturers making the same product use somewhat different processes with different energy requirements and fuel mixes, and that there are limited data on the extent to which various processes are used. Thus, although the goal was to estimate as accurately as possible the national average GHG emissions for the manufacture of each material from virgin and recycled inputs, individual manufacturers will likely have GHG emissions that vary significantly from those estimated here.

2.2 NONENERGY GHG EMISSIONS FROM MANUFACTURING AND RAW MATERIALS ACQUISITION

In addition to GHG emissions from energy use, EPA researchers accounted for three additional sources of GHGs in manufacturing processes:

- When limestone ($CaCO_3$) is converted to lime (CaO), CO_2 is emitted. Significant quantities of lime are used in the production of cement,[11] steel, aluminum, and, to a much lesser extent, office paper.
- CH_4 emissions from natural gas pipelines and processing of natural gas are associated with the manufacture of plastic products.
- PFCs (CF_4 and C_2F_6) are emitted during aluminum smelting.

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[9] U.S. Census Bureau, 2003. *Commodity Flow Survey*. United States Census Bureau. December 2003. Available online at: www.census.gov/prod/ec02/02tcf-usp.pdf.

[10] Available at EPA's Global Warming—Waste, "Background Documents for Solid Waste Management and GHG Report" website: http://www.epa.gov/mswclimate, then follow links to Publications → Reports, Papers, and Presentations → This report → Background Documents.

[11] For the category "concrete" the material being replaced is not the cement, but rather the aggregate (i.e. sand and rock) portion of concrete. However fly ash is used as a cement replacement in concrete, and the nonenergy emissions of the replaced virgin cement are accounted for in estimations for the "fly ash" category.

The process nonenergy GHGs for each material are shown in the second-to-last column of Exhibit 2-3 and Exhibit 2-5 (for manufacture from virgin inputs and recycled inputs, respectively), and are repeated in column "f" of Exhibit 2-2. ORD supplied the nonenergy CO_2 emissions for glass, corrugated cardboard, and newspaper. EPA based the calculation for PFC and CO_2 emissions from aluminum on the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004.*[12]

Nonenergy CO_2 emissions for the other materials, as well as CH_4 emissions, are based on the original analysis supporting the first edition of this report.[13]

2.3 RESULTS

The estimates of the total GHG emissions from raw materials acquisition and manufacturing for each material are shown in Exhibit 2-2, column "g." In order to obtain these estimates, EPA summed the energy-related GHG emissions (column "e") and the nonenergy GHG emissions (column "f"). The estimates in column "g" correspond to the type of inputs that occur during the recycling process: virgin inputs, recycled inputs, or the current mix of virgin and recycled inputs.

The process energy and transportation GHG values for virgin and recycled production are shown in the third-to-last columns of Exhibit 2-3 and Exhibit 2-5, and in the last columns of Exhibit 2-4 and Exhibit 2-6 (the last columns of Exhibit 2-3 and Exhibit 2-5 show the total process energy GHG emissions). The retail transport energy and emission values are presented in Exhibit 2-7.

2.4 LIMITATIONS

There are several limitations to the analysis of the GHG emissions associated with raw materials acquisition and manufacturing, as described below.

The approach used in this analysis provides values for the average GHG emission rates per ton of material produced, not the marginal emission rates per incremental ton produced. In some cases, the marginal emission rates may be significantly different. For example, reducing the production of plastic products from virgin inputs may not result in a proportional decrease in CH_4 emissions from natural gas pipelines and natural gas processing. The operating pressure in natural gas pipelines and the number and size of leaks in the pipeline determine CH_4 emissions from natural gas pipelines. Consequently, the amount of natural gas consumed at one end of the pipeline (e.g., to make plastic) does not affect the level of pipeline CH_4 emissions in a direct, linear way. As another example, long-term reductions in electricity demand could selectively reduce demand for specific fuels, rather than reducing demand for all fuels in proportion to their representation in the current average fuel mix. This analysis estimates average carbon conversion rates largely because the marginal rates are much more difficult to estimate. Nevertheless, EPA believes the average values provide a reasonable approximation of the GHG emissions.

In addition, the analysis assumes that the GHG emissions from manufacturing a given product change in a linear fashion as the percentage of recycled inputs moves from 0 to 100 percent. In other words, the analysis assumes that both the energy intensity and the fuel mix change in linear paths over this range. However, it could be that GHG emissions from manufacturing move in a nonlinear path, (e.g., some form of step function) when the percentage of recycled inputs changes, due to capacity limits in manufacturing or due to the economics of manufacturing processes.

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[12] To estimate aluminum PFC emissions on a per-ton basis, EPA divided the inventory estimates for CF_4 and C_2F_6 emissions from aluminum by total primary aluminum production, yielding units in MTCE/ton.

[13] ICF Consulting. 1994. Memorandum, "Detailed Analysis of Greenhouse Gas Emissions Reductions from Increased Recycling and Source Reduction of Municipal Solid Waste," July 29, p. 48 of the Appendix prepared by FAL, dated July 14, 1994.

The information used in this analysis represents the best available data from published and unpublished industry sources, some of it quite dated. Therefore, the data may not necessarily reflect recent trends in industrial energy efficiency or changes in the fuel mix.

Finally, this static analysis does not consider potential future changes in energy usage per unit of output or alternative energy (e.g., nonfossil) sources. Reductions in energy inputs due to efficiency improvements could occur in either virgin input processes or recycled input processes. Efficiency improvements and switching to alternative energy sources will result directly in GHG emissions reductions and may change the reductions possible through increased recycling or source reduction.

Exhibit 2-1
Carbon Coefficients For Selected Fuels (Per Million Btu)

Fuel Type	Metric Tons of CO_2 from Combustion	kg Carbon Equivalent (CE) from Combustion	Metric Tons of Fugitive CH_4 Emissions	kg CE from Fugitive Methane Emissions	kg CE Emitted
Gasoline	0.07	19.05	0.00002	0.10	19.15
LPG	0.06	16.81	0.00002	0.10	16.91
Distillate Fuel	0.07	19.65	0.00002	0.10	19.75
Residual Fuel	0.08	21.18	0.00002	0.10	21.28
Diesel	0.07	19.65	0.00002	0.10	19.75
Oil/Lubricants	0.07	19.94	0.00002	0.10	20.04
Steam (nonpaper products)	0.07	18.07	0.00011	0.61	18.81
Steam (paper products)	0.05	12.80	0.00004	0.25	13.17
National Average Fuel Mix for Electricity	0.06	15.26	0.00010	0.57	15.83
National Average Fossil Fuel Mix for Electricity	0.08	22.17	0.00015	0.83	23.01
Coal Used for Electricity	0.09	24.80	0.00016	0.92	25.72
Coal Used by Industry (Noncoking Coal)	0.09	25.10	0.00016	0.92	26.02
Petroleum Coke	0.10	27.57	-	-	27.57
Metallurgical Coke	0.11	30.69	-	-	30.69
Natural Gas	0.05	13.62	0.00012	0.70	14.33
Nuclear	0.00	0.84	-	-	0.84
Wastes	0.07	19.42	0.00000	0.01	19.61

Exhibit 2-2
GHG Emissions from the Manufacture of Selected Materials
(MTCE per Ton of Product)

(a)	(b)	(c)	(d)	(e)	(f)			(g)		
			Current Mix[a]		Process Nonenergy Emissions			Average Combined Process and Transportation Energy and Process Nonenergy Emissions		
Type of Product	Virgin Input Combined Process and Transportation Energy Emissions	Recycled Input Combined Process and Transportation Energy Emissions	Percent Recycled Inputs	Combined Process and Transportation Energy Emissions	Virgin Inputs	Recycled Inputs	Current Mix	Virgin Inputs	Recycled Inputs	Current Mix
Aluminum Cans	3.53	0.28	51%	1.87	0.73	0.02	0.37	4.27	0.30	2.24
Steel Cans	0.77	0.27	28%	0.63	0.24	0.24	0.24	1.01	0.51	0.87
Copper Wire	2.02	1.66	5%	2.00	0.00	0.00	0.00	2.02	1.66	2.00
Glass	0.13	0.09	23%	0.12	0.04	0.00	0.03	0.18	0.09	0.16
HDPE	0.48	0.05	10%	0.44	0.05	0.00	0.05	0.54	0.05	0.49
LDPE	0.59	0.05	4%	0.57	0.05	0.00	0.05	0.64	0.05	0.62
PET	0.56	0.05	3%	0.54	0.03	0.00	0.03	0.59	0.05	0.57
Corrugated Cardboard	0.23	0.25	35%	0.23	0.00	0.00	0.00	0.23	0.25	0.24
Magazines/Third-class Mail	0.46	0.46	4%	0.46	0.00	0.00	0.00	0.46	0.46	0.46
Newspaper	0.58	0.34	23%	0.52	0.00	0.00	0.00	0.58	0.34	0.52
Office Paper	0.27	0.37	4%	0.28	0.01	0.00	0.01	0.28	0.37	0.28
Phonebooks	0.68	0.42	0%	0.68	0.00	0.00	0.00	0.68	0.42	0.68
Textbooks	0.60	0.58	4%	0.60	0.00	0.00	0.00	0.60	0.58	0.60
Dimensional Lumber	0.05	0.07	0%	0.05	0.00	0.00	0.00	0.05	0.07	0.05
Medium-density Fiberboard	0.10	0.12	0%	0.10	0.00	0.00	0.00	0.10	0.12	0.10
Mixed Paper[b]										
Broad Def'n (Boxboard "A")	0.32	0.18	23%	0.29	0.00	0.00	0.00	0.32	0.18	0.29
Residential Def'n (Boxboard "B")	0.32	0.18	25%	0.29	0.00	0.00	0.00	0.32	0.18	0.29
Office Def'n (Paper Towels)	0.90	0.00	10%	0.81	0.00	0.00	0.00	0.90	0.00	0.81
Carpet	0.95	NA	0%	0.95	0.14	0.00	0.14	1.09	NA	1.09
Personal Computers	15.10	NA	0%	15.10	0.03	0.00	0.03	15.13	NA	15.13
Clay Bricks	0.08	NA	0%	0.08	0.00	0.00	0.00	0.08	0.00	0.08
Concrete	0.00	0.00	0%	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fly Ash	NA	NA	0%	NA	NA	NA	NA	NA	NA	NA
Tires	1.09	0.45	0%	1.09	NA	NA	0.00	1.09	0.45	1.09

Note that totals may not add due to rounding, and more digits may be displayed than are significant. NA: Not applicable, or in the case of composting of paper, not analyzed.

[a] The current mix of recycled and virgin inputs varies by material type and is based on data from FAL.

[b] For recycled Boxboard, different sets of manufacturing and transportation data. Boxboard "A" and Boxboard "B" differ with respect to their recycled material inputs only (i.e., the proportion of newsprint, corrugated boxes, office paper, and different sets of manufacturing and transportation data).

Explanatory notes: To estimate the GHG emissions from manufacturing, EPA first estimated the process and transportation GHG emissions when 100 pereent virgin inputs, or 100 pereent reeyeled inputs, are used. For eaeh product and eaeh type of input (virgin or recyeled), EPA summed the estimates for process and transportation GHG emissions. Next the EPA researehers estimated the GHG emissions from manufaeturing eaeh material from the eurrent mix of virgin and reeyeled inputs. The researehers began with estimates of the pereentage of reeyeled inputs eurrently used in the manufaeture of eaeh material, as shown in eolumn "d." The team used these pereentages to develop a weighted average value for the GHG emissions assoeiated with the manufaeture of eaeh material from the eurrent mix of virgin and reeyeled inputs. Speeifieally, the researehers used the estimate of the pereentage of reeyeled inputs in the eurrent mix, together with the estimates for GHG emissions from manufaeture using virgin or reeyeled inputs, to develop estimates of GHG emissions from manufaeture using the eurrent mix of virgin and reeyeled inputs (eolumn "e").

Column "f" shows estimates of the proeess nonenergy GHG emissions from manufaeturing. First, this eolumn shows the proeess nonenergy GHG emissions when virgin inputs are used. Then it shows the emissions when reeyeled inputs are used (these values are simply eopied from the final eolumns of Exhibit 2-3 and Exhibit 2-5). Finally, eolumn "f" shows the proeess nonenergy GHG emissions from manufaeturing eaeh produet from the eurrent mix of virgin and reeyeled inputs. The values for the eurrent mix are the weighted averages of the values for virgin and reeyeled inputs, based on the pereentage of reeyeled inputs used in the eurrent mix (as shown in eolumn "d").

The total GHG emissions from manufaeturing are shown in eolumn "g." This eolumn shows total GHG emissions when a produet is manufaetured from virgin or reeyeled inputs, or from the eurrent mix of virgin and reeyeled inputs.

Exhibit 2-3
Process GHG Emissions Per Ton of Product Manufactured from Virgin Inputs

Type of Product	Process Energy (Million Btu)	Average Fuel Mix (in Percent)											Process Energy Emissions (MTCE)	Process Nonenergy Emissions (MTCE)	Total Process Emissions (MTCE)
		Gasoline	LPG	Distillate Fuel	Residual Fuel	Biomass / Hydro	Diesel	Electricity	Coal	Natural Gas	Nuclear	Other			
Aluminum Cans	213.33	0.11	0.01	0.59	1.13	0.03	0.20	88.50	0.69	8.57	0.16	0.02	3.38	0.73	4.11
Steel Cans	31.58	0.21	0.00	5.06	0.35	0.00	0.00	21.02	53.90	19.45	0.00	0.00	0.67	0.24	0.91
Copper Wire	122.52	0.29	0.02	0.77	6.14	0.05	10.82	49.95	2.25	29.38	0.29	0.04	2.00	0.00	2.00
Copper Ingot	109.23	0.00	0.00	0.00	0.00	0.00	21.36	51.24	0.00	27.04	0.00	0.00	1.77	0.00	1.77
Glass	6.49	0.55	0.00	1.45	0.47	0.03	0.00	10.12	7.18	79.95	0.23	0.02	0.10	0.04	0.14
HDPE	28.69	0.00	0.00	0.00	33.14	1.16	0.00	5.64	4.59	51.35	4.00	0.13	0.47	0.05	0.53
LDPE	35.26	0.00	0.00	0.00	32.59	1.56	0.00	7.66	6.15	46.52	5.36	0.17	0.58	0.05	0.63
PET	32.82	0.00	0.00	0.00	36.67	1.62	0.00	7.10	6.42	42.41	5.59	0.18	0.55	0.03	0.58
Corrugated Cardboard	25.13	0.01	0.00	0.02	0.54	61.33	1.20	14.06	15.52	7.31	0.01	0.00	0.19	0.00	0.19
Magazines/Third-class Mail	32.99	0.15	0.01	0.32	8.30	24.27	0.00	25.40	17.11	24.33	0.11	0.01	0.46	0.00	0.46
Newspaper	39.92	0.25	0.00	0.52	0.75	9.09	0.68	54.21	1.75	32.43	0.27	0.04	0.56	0.00	0.56
Office Paper	37.01	0.08	0.00	0.17	4.33	60.53	0.00	13.24	8.92	12.68	0.06	0.01	0.27	0.01	0.27
Phonebooks	39.61	0.18	0.01	0.38	9.99	8.86	0.00	30.56	20.59	29.28	0.13	0.02	0.66	0.00	0.66
Textbooks	35.07	0.18	0.01	0.38	9.96	9.14	0.00	30.47	20.52	29.19	0.13	0.02	0.58	0.00	0.58
Dimensional Lumber	2.53	1.57	0.00	0.00	0.00	32.81	15.99	43.09	0.00	6.53	0.00	0.00	0.03	0.00	0.03
Medium-density Fiberboard	10.18	0.14	0.00	0.38	0.05	51.90	1.26	27.61	0.00	18.68	0.00	0.00	0.08	0.00	0.08
Boxboard	32.26	0.00	0.00	0.00	0.94	59.34	1.36	5.32	24.01	9.02	0.00	0.00	0.29	0.00	0.29
Paper Towels	73.44	0.00	0.00	0.01	1.80	24.89	0.45	28.15	2.93	41.78	0.00	0.00	0.86	0.00	0.86
Carpet	60.32	0.47	0.04	0.67	1.48	0.05	0.00	52.06	0.82	44.10	0.28	0.04	0.92	0.14	1.06
Carpet Padding	107.46	0.41	0.02	0.66	1.38	0.05	0.00	58.81	0.97	37.37	0.30	0.04	1.66	0.52	2.17
Carpet Backing	46.54	0.71	0.02	0.70	0.71	0.05	0.00	60.17	0.77	36.53	0.29	0.04	0.72	0.03	0.75
Personal Computers	945.13	0.14	0.00	0.72	0.38	0.06	0.10	92.42	0.97	5.00	0.35	0.05	15.00	0.03	15.03
Clay Bricks	5.10	0.00	0.00	0.00	0.00	0.00	1.89	39.38	0.00	58.73	0.00	0.00	0.08	0.00	0.08
Concrete	0.05	3.16	0.00	60.42	5.68	0.00	0.00	22.61	1.40	6.74	0.00	0.00	0.00	0.00	0.00
Cement	4.77	0.11	0.01	0.89	0.09	0.00	0.00	9.98	58.24	5.58	0.00	25.11	0.11	0.12	0.24
Injection Molded Auto Parts	113.75	0.40	0.02	0.68	1.13	0.05	0.00	61.19	0.79	35.41	0.30	0.04	1.75	0.51	2.27
Asphalt (Cold Patch)	0.50	1.09	0.74	4.84	10.56	0.04	0.00	22.17	1.05	59.24	0.25	0.04	0.01	0.00	0.01
Steel Sheet	14.60	0.67	0.01	9.42	0.82	0.04	0.00	44.67	1.44	42.61	0.27	0.04	0.23	0.40	0.63
Lead Bullion	19.46	0.16	0.00	0.74	0.92	0.05	0.02	86.11	0.91	10.69	0.34	0.05	0.31	0.01	0.32
CRT Glass	9.16	0.40	0.01	6.98	6.88	0.04	0.00	19.64	2.25	63.52	0.24	0.03	0.14	0.04	0.19
Tires	88.17	0.00	0.48	0.48	0.48	0.00	0.00	11.54	9.62	53.85	0.00	23.08	1.09	0.00	1.09

Exhibit 2-4
Transportation GHG Emissions Per Ton of Product Manufactured from Virgin Inputs

Type of Product	Transportation Energy (Million Btu)	Average Fuel Mix (in Percent)											Transportation Energy Emissions (MTCE)
		Gasoline	LPG	Distillate Fuel	Residual Oil	Biomass/ Hydro	Diesel	Electricity	Coal	Natural Gas	Nuclear	Other	
Aluminum Cans	7.15	0.10	0.08	0.39	80.26	0.05	10.82	0.34	0.87	6.71	0.34	0.05	0.15
Steel Cans	4.60	0.00	0.00	0.00	1.76	0.00	98.24	0.00	0.00	0.00	0.00	0.00	0.09
Copper Wire	0.46	0.09	0.08	0.39	4.16	0.06	87.04	0.02	0.86	6.92	0.34	0.05	0.01
Copper Ingot	3.06	0.00	0.00	0.00	0.00	0.00	72.25	27.75	0.00	0.00	0.00	0.00	0.06
Glass	0.58	0.10	0.08	0.40	2.64	0.04	88.95	0.00	0.89	6.51	0.36	0.03	0.01
HDPE	NA												NA
LDPE	NA												NA
PET	NA												NA
Corrugated Cardboard	1.31	0.05	0.00	0.05	0.27	0.01	98.51	0.00	0.00	1.07	0.04	0.01	0.03
Magazines/Third-class Mail	NA												NA
Newspaper	0.50	0.10	0.08	0.39	3.63	0.05	87.97	0.00	0.86	6.53	0.34	0.05	0.01
Office Paper	NA												NA
Phonebooks	NA												NA
Textbooks	NA												NA
Dimensional Lumber	0.88	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.02
Medium-density Fiberboard	1.01	0.00	0.00	0.00	0.06	0.00	98.10	0.00	0.00	1.84	0.00	0.00	0.02
Boxboard	1.79	0.00	0.00	0.00	0.05	0.00	99.93	0.00	0.00	0.01	0.00	0.00	0.04
Paper Towels	2.07	0.00	0.00	0.00	0.52	0.00	99.46	0.01	0.00	0.02	0.00	0.00	0.04
Carpet	1.36	0.15	0.07	0.40	28.61	0.05	51.89	1.76	0.88	15.83	0.32	0.05	0.03
Carpet Padding	2.15	0.35	0.07	0.16	30.60	0.05	51.59	1.77	0.83	14.22	0.32	0.05	0.04
Carpet Backing	1.36	0.19	0.06	0.38	23.75	0.05	47.13	1.27	0.77	26.07	0.29	0.04	0.03
Personal Computers	5.03	0.10	0.08	0.41	60.22	0.05	30.64	0.29	0.86	7.03	0.33	0.05	0.10
Clay Bricks	0.03	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Concrete	0.19	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Cement	0.10	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Injection Molded Auto Parts	1.51	0.16	0.07	0.38	43.15	0.05	35.19	2.51	0.81	17.33	0.30	0.04	0.03
Asphalt (Cold Patch)	0.20	0.11	0.08	0.40	41.98	0.05	47.26	2.34	0.86	6.54	0.33	0.05	0.00
Steel Sheet	1.41	0.10	0.08	0.39	13.18	0.05	78.30	0.04	0.85	6.64	0.32	0.05	0.03
Lead Bullion	0.63	0.10	0.08	0.41	5.10	0.05	86.35	0.01	0.86	6.66	0.32	0.05	0.01
CRT Glass	0.28	0.35	0.08	0.11	3.85	0.05	87.93	0.00	0.85	6.42	0.32	0.05	0.01
Tires	NA												

Note that for some materials, transportation data were included in the process energy estimates and not provided separately, denoted by "NA" in this table.

Exhibit 2-5
Process GHG Emissions Per Ton of Product Manufactured from Recycled Inputs

Type of Product	Process Energy (Million Btu)	Average Fuel Mix (in Percentage)											Process Energy Emissions (MTCE)	Process Nonenergy Emissions (MTCE)	Total Process Emissions (MTCE)
		Gasoline	LPG	Distillate Fuel	Residual Fuel	Biomass/ Hydro	Diesel	Electricity	Coal	Natural Gas	Nuclear	Other			
Aluminum Cans	16.59	0.34	0.01	0.49	4.28	0.04	0.00	45.10	0.72	48.71	0.27	0.04	0.26	0.02	0.28
Steel Cans	11.78	0.01	0.17	0.07	0.03	0.00	0.00	77.28	0.65	21.80	0.00	0.00	0.18	0.24	0.42
Copper Wire	101.05	0.33	0.01	0.81	6.87	0.05	0.00	52.65	2.53	36.42	0.30	0.04	1.61	0.00	1.61
Copper Ingot	8.90	0.00	0.00	18.98	0.00	0.00	0.00	27.70	0.09	51.23	0.00	2.00	0.14	0.00	0.14
Glass	4.32	0.55	0.00	0.39	0.26	0.03	0.00	5.10	0.54	92.91	0.21	0.02	0.06	0.24	0.30
HDPE	4.17	0.03	0.03	1.05	1.24	12.48	0.05	33.21	0.02	20.34	0.09	31.44	0.04	0.00	0.04
LDPE	4.17	0.03	0.03	1.05	1.24	12.48	0.05	33.21	0.02	20.34	0.09	31.44	0.04	0.00	0.04
PET	4.17	0.03	0.03	1.05	1.24	12.48	0.05	33.21	0.02	20.34	0.09	31.44	0.04	0.00	0.04
Corrugated Cardboard	11.73	0.01	0.05	0.05	0.66	0.00	0.31	51.11	38.40	9.40	0.01	0.00	0.23	0.00	0.23
Magazines/Third-class Mail	31.97	0.16	0.01	0.32	8.45	22.85	0.00	25.87	17.43	24.79	0.11	0.01	0.45	0.00	0.45
Newspaper	21.98	0.30	0.00	0.58	0.30	0.05	0.00	57.75	1.09	39.59	0.30	0.04	0.34	0.00	0.34
Office Paper	20.12	0.20	0.01	0.42	10.96	0.02	0.00	33.53	22.58	32.12	0.14	0.02	0.37	0.00	0.37
Phonebooks	22.02	0.20	0.01	0.42	10.96	0.02	0.00	33.53	22.58	32.12	0.14	0.02	0.40	0.00	0.40
Textbooks	33.51	0.21	0.01	0.60	10.02	8.38	0.00	30.40	20.61	29.57	0.17	0.02	0.56	0.00	0.56
Dimensional Lumber	3.17	0.00	0.00	0.00	0.00	0.00	23.61	76.39	0.00	0.00	0.00	0.00	0.05	0.00	0.05
Medium-density Fiberboard Made from Reused Dimensional Lumber	10.99	0.13	0.00	0.35	0.04	48.05	8.56	25.56	0.00	17.29	0.00	0.00	0.09	0.00	0.09
Boxboard Made from Broad Definition of Mixed Paper	10.45	0.00	0.00	13.57	0.00	0.00	0.00	13.78	15.38	57.27	0.00	0.00	0.18	0.00	0.18
Boxboard Made from Residential Definition of Mixed Paper	10.45	0.00	0.00	13.57	0.00	0.00	0.00	13.78	15.38	57.27	0.00	0.00	0.18	0.00	0.18
Paper Towels Made from Recovered File Stock	51.69	0.00	0.00	0.00	0.45	6.94	0.15	36.32	0.98	55.14	0.00	0.00	0.73	0.00	0.73
Carpet Padding	2.14	0.12	0.00	0.68	0.26	0.06	0.00	95.36	0.95	2.15	0.36	0.05	0.03	0.00	0.03
Carpet Backing	23.27	0.12	0.00	0.68	0.26	0.06	0.00	95.39	0.95	2.15	0.35	0.05	0.37	0.00	0.37
Concrete	0.04	0.00	0.00	0.00	0.00	0.00	54.23	45.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Injection Molded Auto Parts from Nylon Carpet	20.24	0.12	0.00	0.68	0.26	0.06	0.00	95.45	0.95	2.08	0.36	0.05	0.32	0.00	0.32
Asphalt (Cold Patch)	5.49	0.20	0.10	0.85	1.52	0.05	0.00	87.09	0.91	8.89	0.34	0.05	0.09	0.00	0.09
Steel Sheet	12.53	0.23	0.00	0.64	0.30	0.05	0.00	72.60	1.40	24.41	0.32	0.04	0.20	0.01	0.20
Lead Bullion	19.50	0.20	0.00	0.70	0.90	0.06	0.00	86.68	0.92	10.16	0.34	0.05	0.31	0.00	0.31
CRT Glass	7.29	0.36	0.01	6.48	6.50	0.04	0.00	29.64	0.69	55.99	0.26	0.04	0.11	0.00	0.11
Tires	36.21	0.00	0.48	0.48	0.48	0.00	0.00	11.54	9.62	53.85	0.00	23.08	0.45	0.00	0.45

Exhibit 2-6
Transportation GHG Emissions Per Ton of Product Manufactured from Recycled Inputs

Type of Product	Transportation Energy (Million Btu)	Average Fuel Mix (in Percentage)											Transportation Energy Emissions (MTCE)
		Gasoline	LPG	Distillate Fuel	Residual Oil	Biomass/ Hydro	Diesel	Elec-tricity	Coal	Natural Gas	Nuclear	Other	
Aluminum Cans	1.01	0.10	0.08	0.40	3.76	0.05	87.87	0.00	0.85	6.53	0.32	0.05	0.02
Steel Cans	4.03	0.00	0.00	0.00	0.01	0.00	99.99	0.00	0.00	0.00	0.00	0.00	0.08
Copper Wire	2.17	0.10	0.08	0.39	3.84	0.05	87.67	0.00	0.86	6.63	0.33	0.05	0.04
Copper Ingot	1.89	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.04
Glass	0.34	0.10	0.08	0.41	2.59	0.04	89.01	0.00	0.89	6.51	0.35	0.03	0.01
HDPE	0.08	0.00	0.00	0.00	56.50	0.00	5.96	2.53	0.00	35.01	0.00	0.00	0.00
LDPE	0.08	0.00	0.00	0.00	56.50	0.00	5.96	2.53	0.00	35.01	0.00	0.00	0.00
PET	0.08	0.00	0.00	0.00	56.50	0.00	5.96	2.53	0.00	35.01	0.00	0.00	0.00
Corrugated Cardboard	0.80	0.05	0.00	0.05	0.22	0.01	98.55	0.00	0.00	1.07	0.04	0.00	0.02
Magazines/Third-class Mail	NA												
Newspaper	0.03	0.10	0.08	0.39	3.75	0.05	87.87	0.00	0.86	6.53	0.32	0.05	0.00
Office Paper	NA												
Phonebooks	NA												0.00
Textbooks	NA												0.00
Recycled Lumber from Dimensional Lumber	0.97	0.00	0.00	0.00	0.00	0.00	100.06	0.00	0.00	0.00	0.00	0.00	0.02
Medium-density Fiberboard Made from Reused Dimensional Lumber	1.27	0.00	0.00	0.00	0.05	0.00	98.46	0.00	0.00	1.47	0.00	0.00	0.02
Boxboard Using the "Broad Definition" for Mixed Paper	0.19	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Boxboard Using the "Single-Family Residential Definition" for Mixed Paper	0.19	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Paper Towels Using "Office Paper" for Mixed Paper	0.44	0.00	0.00	0.00	2.31	0.00	97.58	0.06	0.00	0.08	0.00	0.00	0.01
Carpet Padding	1.05	0.10	0.08	0.38	3.64	0.05	88.03	0.00	0.84	6.51	0.33	0.05	0.02
Carpet Backing	1.05	0.10	0.08	0.38	3.64	0.05	88.03	0.00	0.84	6.51	0.33	0.05	0.02
Concrete	0.09	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Injection Molded Auto Parts from Nylon Carpet	1.05	0.10	0.08	0.38	3.82	0.05	87.84	0.00	0.86	6.49	0.32	0.05	0.02
Asphalt (Cold Patch)	0.98	0.10	0.08	0.39	14.71	0.05	76.21	0.69	0.86	6.54	0.33	0.05	0.02
Steel Sheet	0.67	0.09	0.08	0.39	3.97	0.05	87.56	0.00	0.87	6.61	0.33	0.05	0.01
Lead Bullion	4.01	0.10	0.08	0.39	3.80	0.05	87.86	0.00	0.85	6.48	0.33	0.05	0.08
CRT Glass	5.28	0.05	0.04	0.20	1.89	0.03	93.85	0.00	0.42	3.33	0.17	0.02	0.10
Tires	NA												

Exhibit 2-7
Retail Transport Energy and Emissions

Material Type	Transportation Energy (Million Btu Per Ton of Product)	Transportation Emission Factors (MTCE per Ton of Product)
Aluminum Cans	0.31	0.01
Steel Cans	0.31	0.01
Glass	1.02	0.02
HDPE	0.48	0.01
LDPE	0.48	0.01
PET	0.48	0.01
Corrugated Cardboard	0.32	0.01
Magazines/Third-class Mail	0.26	0.01
Newspaper	0.26	0.01
Office Paper	0.26	0.01
Phonebooks	1.02	0.02
Textbooks	1.02	0.02
Dimensional Lumber	0.12	0.00
Medium-density Fiberboard	0.32	0.01

3. SOURCE REDUCTION AND RECYCLING

This chapter presents estimates of GHG emissions and carbon sequestration resulting from source reduction and recycling of 21 manufactured materials: aluminum cans, steel cans, copper wire, glass, plastic containers (LDPE, HDPE, and PET), corrugated cardboard, magazines/third-class mail, newspaper, office paper, phonebooks, textbooks, dimensional lumber, medium-density fiberboard, carpet, personal computers, clay bricks, concrete, fly ash, and tires. It also presents estimates for s three definitions of mixed paper (broad, residential, and office). Also included in this chapter is a discussion of forest carbon sequestration, an important input in calculating the emission benefits of paper product source reduction and recycling. The chapter is organized as follows:

Section 3.1 Emission benefits of source reduction;

Section 3.2 Emission benefits of recycling;

Section 3.3 Open-loop recycling;

Section 3.4 Source reduction through material substitution;

Section 3.5 Implications and methodology of calculating forest carbon sequestration; and

Section 3.6 Limitations of the analyses presented in this chapter.

To estimate GHG emissions associated with source reduction and recycling (and other MSW management options), EPA used a baseline scenario in which the material is manufactured from the current mix of virgin and recycled inputs, but has not yet been disposed of or recycled. Thus, the baseline for each material already incorporates some emissions from raw materials acquisition and manufacturing using the current mix of virgin and recycled inputs. Using this measurement convention, it follows that source reduction[1] reduces GHG emissions from the raw material acquisition and manufacturing phase of the life cycle for all materials. Moreover, source reduction of paper results in forest carbon sequestration (as discussed in Section 3.5 below).

Manufacturing from recycled inputs generally requires less energy, and thus lower GHG emissions, than manufacturing from virgin inputs. The recycling analysis indicates that recycling reduces GHG emissions for each of the materials studied.

3.1 GHG IMPLICATIONS OF SOURCE REDUCTION

When a material is source reduced (i.e., less of the material is made), GHG emissions associated with making the material and managing the postconsumer waste are avoided. As discussed above, under the measurement convention used in this analysis, source reduction has (1) negative raw material and manufacturing GHG emissions (i.e., it avoids baseline emissions attributable to current production); (2) forest carbon sequestration benefits in the case of paper products (also treated as negative emissions, as estimated in Section 3.5); and (3) zero waste management GHG emissions. Exhibit 3-1 presents the GHG implications of source reduction.

[1] In this analysis, the values reported for source reduction apply to material lightweighting or extension of a product's useful life. EPA assumes no substitution by another material or product; therefore, EPA assumes no offsetting GHG emissions from another material or product. Thus, the data do not directly indicate GHG effects of source reduction that involves material substitution. Considerations for estimating the GHG effects of material substitution are presented in Section 3.4 below.

In order to compare source reduction to other solid waste management alternatives, EPA compared the GHG reductions from source reduction to the life-cycle GHG emissions of another solid waste management option (e.g., landfilling). This approach enables policymakers to evaluate, on a per-ton basis, the overall difference in GHG emissions between (1) source reducing 1 ton of material, and (2) manufacturing and then managing (postconsumer) 1 ton of the same material. Such comparisons are made in the Executive Summary and in Chapter 8 of this report. For most materials, source reduction has lower GHG emissions than the other waste management options. The most notable exceptions are for aluminum cans and carpet, where source reduction benefits are high, but recycling benefits are higher.

3.2 GHG IMPLICATIONS OF RECYCLING

When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed of and managed as waste.[2] As with source reduction of paper products, recycling of paper also results in forest carbon sequestration.

Most of the materials considered in this analysis are modeled as being recycled in a closed loop (e.g., newspaper is recycled into new newspaper). However, a few materials are recycled in an open loop, including several paper types (under the general heading of mixed paper)[3], fly ash, carpet, and personal computers (i.e., they are recycled into a product other than themselves); concrete and copper wire are recycled in a quasi-open loop. Mixed paper is included because it is recycled in large quantities and is an important class of scrap material in many recycling programs. However, presenting a single definition of mixed paper is difficult because each mill using recovered paper defines its own supply, which varies with the availability and price of different grades of paper.

For the purpose of this report, EPA identified three definitions for mixed paper: broad, office, and residential. To assist recyclers in determining which definition corresponds most closely to mixed paper streams they manage, the composition of each is presented in Exhibit 3-2. The broad definition of mixed paper includes almost all printing-writing paper, folding boxes, and most paper packaging. Mixed paper from offices includes copier and printer paper, stationary and envelopes, and commercial printing. The typical mix of papers from residential curbside pick-up includes high-grade office paper, magazines, catalogues, commercial printing, folding cartons, and a small amount of old corrugated containers. The broad and residential definitions of mixed paper can be remanufactured via an open loop into recycled boxboard. Mixed paper from offices is typically used to manufacture commercial paper towels.

Fly ash is a byproduct of coal combustion that is used as a cement replacement in concrete. The analysis for carpet is based on nylon broadloom residential carpet and is a composite of several material types, specifically nylon carpet fiber, polypropylene carpet backing, and adhesive of synthetic latex and limestone. It is recycled into carpet pad, carpet backing, and molded auto parts. PCs are also composites, consisting mostly (by weight) of steel, glass, plastics, aluminum, lead, and copper. They are recycled into steel sheet, glass for cathode ray tubes (CRTs), asphalt, aluminum sheet (equivalent to aluminum cans in this analysis), lead bullion, and copper wire. Copper wire itself is not recycled specifically into new copper wire, but is used in the manufacture of copper alloys. Concrete is crushed and used in place of virgin aggregate in the production of new concrete.

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[2] Note that when paper is manufactured from recycled inputs, the amount of paper sludge produced is greater than when paper is made from virgin inputs. This difference is because recycled paper has more short fibers, which must be screened out. EPA made a preliminary estimate of the GHG emissions from paper sludge managed in landfills; the results indicated that net GHG emissions (i.e., CH_4 emissions minus carbon sequestration) were close to zero. Because the emissions are small and highly uncertain, no quantitative estimate is included in this report.

[3] This report also includes estimates for mixed MSW, mixed plastics, mixed organics, and mixed recyclables, i.e., a mixture of the principal paper, metal, and plastic materials that are recycled. These other mixed materials are discussed in Chapter 8.

When any material is recovered for recycling, some portion of the recovered material is unsuitable for use as a recycled input. This portion is discarded either in the recovery stage or in the remanufacturing stage. Consequently, less than 1 ton of new material generally is made from 1 ton of recovered material. Material losses are quantified and translated into loss rates. In this analysis, EPA used estimates of loss rates provided by FAL for steel, dimensional lumber, and medium-density fiberboard (the same materials for which FAL's energy data were used, as described in Chapter 2). ORD provided loss rates for the other materials. These values are shown in Exhibit 3-3

GHG emission reductions associated with remanufacture using recycled inputs are calculated by taking the difference between (1) the GHG emissions from manufacturing a material from 100 percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the material (accounting for loss rates) from 100 percent virgin inputs.

The results of the analysis are shown in Exhibit 3-8. In this exhibit, for each material the differences between manufacture from virgin and recycled inputs for (1) energy-related GHG emissions (both in manufacturing processes and transportation), (2) process nonenergy-related GHG emissions, and (3) forest carbon sequestration are presented. The method of accounting for loss rates yields estimates of GHG emissions on the basis of MTCE per short ton of material recovered for recycling (rather than emissions per ton of material made with recycled inputs).

EPA recognizes that some readers may find it more useful to evaluate recycling in terms of tons of recyclables as marketed (after sorting and processing) rather than tons of materials recovered. To adjust the emission factors reported in Exhibit 3-8 for that purpose, one would scale up the recycled input credits shown in columns "b" and "d" of that exhibit by the ratio of manufacturing loss rate to total loss rate (i.e., Exhibit 3-3 column "c" divided by column "d").

Another way that recycling projects can be measured is in terms of changes in recycled content of products. To evaluate the effects of such projects, one could use the following algorithm:[4]

(Eqn. 1)

$$T_{recyc} = T_{prod} \times (RC_p - RC_i)/L$$

Where,

T_{recyc} = tons of material recycled, as collected
T_{prod} = tons of the product with recycled content
RC_p = recycled content (in percent) after implementation of the project
RC_i = recycled content (in percent) initially
L = loss rate (from Exhibit 3-3, column "d")

Then, one could use the emission factors in this report directly with the tons of material recycled (as collected) to estimate GHG emissions.

[4] This approach would apply only where the products with recycled content involve the same "recycling loop" as the ones on which the values in this report are based (e.g., aluminum cans are recycled in a closed loop into more aluminum cans).

Exhibit 3-1
GHG Emissions for Source Reduction
(MTCE/Ton of Material Source Reduced)

Material	Avoided GHG Emissions from Raw Materials Acquisition and Manufacturing		Postconsumer	Changes in Forest Carbon Storage		Net Emissions For Current Mix of Inputs	Net Emissions For 100% Virgin Inputs
	For Current Mix of Inputs	For 100% Virgin Inputs		For Current Mix Of Inputs	For 100% Virgin Inputs		
Aluminum Cans	-2.24	-4.27	0.00	0.00	0.00	-2.24	-4.27
Steel Cans	-0.87	-1.01	0.00	0.00	0.00	-0.87	-1.01
Copper Wire	-2.00	-2.02	0.00	0.00	0.00	-2.00	-2.02
Glass	-0.16	-0.18	0.00	0.00	0.00	-0.16	-0.18
HDPE	-0.49	-0.54	0.00	0.00	0.00	-0.49	-0.54
LDPE	-0.62	-0.64	0.00	0.00	0.00	-0.62	-0.64
PET	-0.57	-0.59	0.00	0.00	0.00	-0.57	-0.59
Corrugated Cardboard	-0.24	-0.23	0.00	-1.29	-1.98	-1.52	-2.21
Magazines/Third-class Mail	-0.46	-0.46	0.00	-1.90	-1.98	-2.36	-2.44
Newspaper	-0.52	-0.58	0.00	-0.80	-1.04	-1.33	-1.62
Office Paper	-0.28	-0.28	0.00	-1.90	-1.98	-2.18	-2.26
Phonebooks	-0.68	-0.68	0.00	-1.04	-1.04	-1.72	-1.72
Textbooks	-0.60	-0.60	0.00	-1.90	-1.98	-2.50	-2.58
Dimensional Lumber	-0.05	-0.05	0.00	-0.50	-0.50	-0.55	-0.55
Medium-density Fiberboard	-0.10	-0.10	0.00	-0.50	-0.50	-0.60	-0.60
Carpet	-1.09	-1.09	0.00	0.00	0.00	-1.09	-1.09
Personal Computers	-15.13	-15.13	0.00	0.00	0.00	-15.13	-15.13
Clay Bricks	-0.08	-0.08	0.00	0.00	0.00	-0.08	-0.08
Concrete	NA	NA	NA	NA	NA	NA	NA
Fly Ash	NA	NA	NA	NA	NA	NA	NA
Tires	-3.81	-3.81	0.00	0.00	0.00	-3.81	-3.81

Exhibit 3-2
Composition of Mixed Paper Categories (As a Percentage of Total)

Paper Grade	All Paper and Paperboard in MSW [a]	Mixed Paper: Broad Definition [b]	Mixed Paper: Office [c]	Mixed Paper: Single-Family Residential [d]
Uncoated groundwood paper	4.9%	4.9%	7.9%	2.2%
Coated free sheet paper	5.0%	12.0%	13.9%	11.5%
Coated groundwood paper	4.3%	11.5%	30.7%	17.7%
Uncoated free sheet paper	14.3%	37.6%	41.6%	18.4%
Cotton fiber paper	0.1%	0.4%	1.8%	0.2%
Bleached bristols	1.5%	3.9%	4.1%	2.8%
Newspaper	13.3%	2.9%		2.9%
Virgin corrugated boxes	29.6%			12.2%
Recycled corrugated boxes	6.8%			2.8%
Unbleached kraft folding boxes	1.5%	5.7%		4.1%
Bleached kraft folding boxes	2.8%	5.7%		5.8%
Recycled folding boxes	3.0%	7.9%		8.0%
Bleached bags and sacks	0.4%	1.0%		1.6%
Unbleached bags and sacks	2.1%	5.6%		9.0%
Unbleached wrapping paper	0.1%	0.2%		
Converting paper	0.3%			
Special industrial paper	1.3%			
Other paperboard	2.5%			
Paper plates and cups	1.2%			
Tissue, towels	3.9%			
Set-up boxes	0.3%	0.7%		0.6%
Other paper packaging	0.8%			
Totals	100.0%	100.0%	100.0%	100.0%

[a] All grades of paper and paperboard in MSW.
[b] Excludes newspaper, old corrugated containers, tissue produce, paper plates and cups, converting and special industrial papers, nonpackaging paperboard such as album covers and posterboard, and paper labels.
[c] Includes the high-grade papers (ledger and computer printout) as well as stationery, mail, magazines, and manila folders. Could be recovered as "file stock."
[d] Represents a typical collection of mixed paper from a single-family curbside program. Includes printing-writing papers, corrugated boxes, folding cartons, and bags and sacks.
Source: Working papers prepared by Franklin Associates, Ltd., October 1997.

In order to compare GHG emissions from recycling to those attributable to another solid waste management option such as landfilling, EPA compared the total GHG emissions from recycling the material to the GHG emissions from managing the disposal of the same material under another waste management option. The baseline for a given material (which includes GHG emissions from raw materials acquisition and manufacturing for the current mix of virgin and recycled inputs) for both options is the same. Overall, because recycling reduces the amount of energy required to manufacture materials (as compared to manufacture with virgin inputs) and leads to avoided process nonenergy GHG emissions, recycling has lower GHG emissions than all other waste management options except for source reduction.

Exhibit 3-3
Loss Rates For Recovered Materials

(a) Material	(b) Percent of Recovered Materials Retained in the Recovery Stage	(c) Tons of Product Made per Ton of Recycled Inputs In the Manufacturing Stage	(d) (d = b × c) Tons of Product Made Per Ton Recovered Materials	(e) Data Source[a]
Aluminum Cans	100	0.93	0.93	FAL & ORD
Steel Cans	100	0.98	0.98	FAL
Copper Wire	82	0.99	0.81	FAL
Glass	90	0.98	0.88	FAL & ORD
HDPE	90	0.86	0.78	FAL & ORD
LDPE	90	0.86	0.78	FAL & ORD
PET	90	0.86	0.78	FAL & ORD
Corrugated Cardboard	100	0.93	0.93	FAL & ORD
Magazines/Third-class Mail	95	0.71	0.67	FAL & ORD
Newspaper	95	0.94	0.90	FAL & ORD
Office Paper	91	0.66	0.60	FAL & ORD
Phonebooks	95	0.71	0.68	FAL & ORD
Textbooks	95	0.69	0.66	FAL & ORD
Dimensional Lumber	88	0.91	0.80	FAL
Medium-density Fiberboard	88	0.91	0.80	FAL
Tires[b]	90	0.86	0.78	NA

[a] FAL provided data for column (b), while ORD provided data for column (c).
[b] HDPE used as a proxy.
Explanatory notes: The value in column "b" accounts for losses such as recovered newspapers that were unsuitable for recycling because they were too wet. Column "c" reflects process waste losses at the manufacturing plant or mill. Column "d" is the product of the values in Columns "b" and "c."

3.3 OPEN-LOOP RECYCLING

Unlike most of the materials for which EPA has developed recycling GHG emission factors (e.g., aluminum cans, glass bottles), some materials are assumed to be recycled in an "open loop"—i.e., carpet is recycled into new products other than new carpet. Therefore, the GHG benefits of some material recycling result from the avoided emissions associated with the manufacture of the *secondary* products that the material is recycled into (since the recycling would affect only the production of the secondary products). In applying this method, EPA considered only the GHG benefit for one generation of recycling (i.e., future benefits from recycling the secondary products into additional products were not included). To calculate the GHG benefits of recycling the primary material, EPA compared the difference in emissions associated with manufacturing one ton of each of the secondary products from virgin versus recycled materials, after accounting for losses that occur in the recycling process. The results for each of the secondary products then were weighted by the appropriate material-flow distribution to obtain a composite emission factor for recycling the primary material type. Materials that are recycled in an open-loop fashion within EPA's life-cycle methodology are mixed paper and corrugated cardboard, copper wire, carpet, personal computers, and concrete.

The secondary product resulting from recycling mixed paper is typically boxboard. This use of mixed paper is due to quality constraints related to a broad mixture of paper types that include newsprint, office paper, coated paper, and corrugated paper. The pulp fibers obtained from mixed paper are well suited for lower grade forest product such as cardboard. For the purposes of this methodology, EPA assumed that 100 percent of recycled mixed paper is utilized to produce boxboard. When corrugated

cardboard is recycled, it is assumed that 74 percent is used to produce boxboard and the remaining 26 percent is utilized to produce corrugated cardboard. In this sense corrugated cardboard is recycled in a partial open loop. Data for creating the open loops for mixed paper and corrugated cardboard were obtained through consultation with the Recycled Paper Trade Association (RPTA).

Secondary products resulting from carpet recycling include carpet pad, molded products, and carpet backing. Carpet pad is used as a cushion layer between the carpet and the floor, which provides thermal and acoustical insulation, and resilience. Molded products for automobiles are used in a wide range of applications, from air intake assemblies to headrests. The carpet backing produced from recycled carpet is generally used to secure the yarn and provide dimensional stability to commercial carpeting. While current information on this subject is not readily available, the use of recycled material is believed to have become both higher and more widespread. An advantage to recycling carpet into backing is that it uses 100 percent of the materials from the recovered carpet, thereby avoiding a solid waste stream from the recycling process. For details on the recycling life-cycle analysis for carpet, please review the *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Carpet and Personal Computers.*[5]

When PCs are recycled, they may be recycled into asphalt, steel sheet, lead bullion, CRT glass, copper wire, and aluminum sheet. Recovered plastic can be utilized as a filler component in the production of asphalt for road construction. Steel and aluminum sheet are used to produce a wide range of materials from auto parts to cookware. Recovered CRT glass can be utilized for the production of new CRT screens or processed to recover lead bullion that can be used to produce items such as batteries and x-ray shielding. Copper wire can be utilized in various electrical applications depending on its grade. For details on the recycling life-cycle analysis for personal computers, please review the *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Carpet and Personal Computers.*[6]

Copper wire is the most common form of unalloyed copper recycled from a municipal solid waste perspective. Given the very high virgin content of copper wire (due to purity standards), it is likely that recovered copper wire would in most cases go into lower grade copper alloys.[7] Therefore, the most accurate approach would be to determine the energy/emissions associated with the production of smelted copper (ingot), rather than finished copper wire. For details on the recycling life-cycle analysis for copper wire, please review the *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Copper Wire.*[8]

When concrete structures are demolished, the waste concrete can be crushed and reused in place of virgin aggregate. Doing so reduces the GHG emissions associated with producing concrete using virgin aggregate material. Virgin aggregates, which include crushed stone, gravel, and sand, are used in a wide variety of construction applications, such as road base, fill, and as an ingredient in concrete and asphalt pavement. For details on the recycling life-cycle analysis for concrete, please review the *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Clay Brick Reuse and Concrete Recycling.*[9]

Coal-based electricity generation results in the production of significant quantities of coal combustion products (CCPs). Fly ash is a CCP that possesses unique characteristics that allow it to be

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[5] Available at the EPA, Global Warming—Waste, "Solid Waste Management and Greenhouse Gases" website. Go to: http://www.epa.gov/mswclimate, then follow links to Publications → Reports, Papers, and Presentations → This report → Background Documents.

[6] Ibid.

[7] CDA, 2003. *Technical Report: Copper, Brass, Bronze. The U.S. Copper-base Scrap Industry and Its Byproducts.* Copper Development Association, Inc.

[8] Available at the EPA, Global Warming—Waste, "Solid Waste Management and Greenhouse Gases" website. Op cit.

[9] Ibid.

utilized as a substitute for Portland cement in making concrete. Through the reuse of fly ash, the GHG emissions associated with the production of Portland cement are avoided. For details on the recycling life-cycle analysis for concrete, please review the *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Fly Ash Used as a Cement Replacement in Concrete.*[10]

3.4 SOURCE REDUCTION THROUGH MATERIAL SUBSTITUTION

As noted above, the analysis of source reduction is based on an assumption that source reduction is achieved by practices such as lightweighting, double-sided copying, and material reuse. However, it is also possible to source reduce one type of material by substituting another material. Analyzing the GHG impacts of this type of source reduction becomes more complicated. Essentially, one would need to estimate the *net* GHG impacts of (1) source reduction of the original material, and (2) manufacture of the substitute material and its disposal fate. A quantitative analysis of source reduction with material substitution was beyond the scope of this report because of the large number of materials that could be substituted for the materials analyzed in this report (including composite materials, e.g., a composite of paper and plastic used in juice boxes) and the need for application-specific data. Where both the original material and the substitute material are addressed in this report, however, the GHG impacts of source reduction with material substitution may be estimated.

The estimate would be based on (1) the data provided in this report for the material that is source reduced; (2) the mass substitution rate for the material that is substituted; and (3) data in this report for the material substituted. The mass substitution rate is the number of tons of substitute material used per ton of original material source reduced. Note, however, that in calculating the mass substitution rate, one should account for any difference in the number of times that a product made from the original material is used prior to waste management, compared to the number of times a product made from the substitute material will be used prior to waste management.

To estimate the GHG impacts of source reduction with material substitution (per ton of material source reduced), one should consider the following: a specific baseline scenario, including waste management; an alternative scenario, involving the substitute material and a waste management method; the number of tons of material used in each scenario, using the mass substitution rate; the net GHG emissions for the baseline; the GHG impacts of source reduction of the original material; the GHG impacts of manufacturing the substitute material; and the GHG impacts of waste management for the substitute material. Among other factors, these considerations will allow for a comparison of net GHG emissions from source reduction with material substitution to the baseline.

3.5 FOREST CARBON SEQUESTRATION

As forests are planted and allowed to grow, they absorb atmospheric CO_2 and store it in the form of cellulose and other materials. When the rate of uptake exceeds the rate of release, carbon is said to be *sequestered.* On the other hand, when trees are cleared and processed or burned, carbon is released.

When paper and wood products are recycled or source reduced, trees that would otherwise be harvested are left standing. In the short term, this reduction in harvesting results in a larger quantity of carbon remaining sequestered, because the standing trees continue to store carbon, whereas the manufacture and use of paper and wood products tend to release carbon.[11] In the long term, some of the short-term benefits disappear as market forces result in less planting of new managed forests than would

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[10] Ibid.

[11] The forest carbon inventory in any year equals the carbon inventory the year before, plus net growth, minus harvests, minus decay. Thus, when harvests are reduced, the inventory increases. However when inventories become high relative to the carrying capacity of the land, the rate of growth decreases because net growth (the rate at which growth exceeds decay) declines.

otherwise occur, so that there is comparatively less forest acreage in trees that are growing rapidly (and thus sequestering carbon rapidly).

In the United States, uptake by forests has long exceeded release, influenced by forest management activities and the reforestation of previously cleared areas. This net sequestration of carbon in forests represents a large and important process. EPA estimated that the annual net CO_2 flux (i.e., the excess of uptake minus release) in U.S. forests was about 213 MMTCE in 2004,[12] offsetting about 8 percent of U.S. energy-related CO_2 emissions. In addition, about 16 million metric tons of carbon was stored in wood products currently in use (e.g., wood in building structures and furniture, paper in books and periodicals). Considering the effect of forest carbon sequestration on U.S. net GHG emissions, it was clear that a thorough examination was warranted for this study.

EPA worked with the U.S. Department of Agriculture Forest Service (USDA-FS) to use models of the U.S. forest sector to estimate the amount of forest carbon sequestration per incremental ton of paper reduced and recycled. These USDA-FS models and data sets are the most thoroughly documented and peer-reviewed models available for characterizing and simulating the species composition, inventory, and growth of forests, and they have been used to analyze GHG mitigation in support of a variety of policy analyses conducted by the Forest Service, so they represent the current state-of-the-art.

EPA used an approach that modeled (1) the effect of incremental recycling on wood harvests, and (2) the change in forest carbon stocks as a function of marginal changes to harvest rates, using the FORCARB II model, and combined the two components to estimate the effect of recycling on forest carbon storage. EPA found that increased recycling of paper products resulted in incremental forest carbon storage of about 0.55 MTCE per ton of paper recovered for mechanical pulp papers and 0.83 MTCE per ton of paper recovered for chemical pulp papers. Papers made from mechanical pulp include newspaper, telephone books, and magazines/third-class mail; papers made from chemical pulp include office paper, corrugated cardboard, and textbooks. The approach to modeling the impact of source reduction and recycling on forest carbon stocks has changed since the last edition of this report was published. The revised approach includes the use of updated USDA-FS models and the differentiation of chemical and mechanical pulp papers.

The USDA-FS models do not directly estimate the effect of source reduction on forest carbon storage. To derive these estimates, EPA evaluated the mix of virgin and recycled inputs used to manufacture each material. As described later, this mix is different for each product. The resulting carbon sequestration rates are 1.04 MTCE per ton for mechanical pulp papers to 1.98 MTCE per ton for chemical pulp papers for 100 percent virgin inputs, and they range from 0.80 to 1.90 MTCE per ton for various paper grades for the current mix of inputs.

3.5.1 Effect of Paper Recovery on Pulpwood Harvest

Several earlier USDA-FS efforts have analyzed the relationship between paper recovery rates and pulpwood harvests, based on data compiled by the American Forest and Paper Association (AF&PA) and the Forest Resources Association (FRA). AF&PA collects information on the mass of recovered paper and wood pulp consumed[13] and paper and paperboard production.[14] FRA publishes information on pulpwood receipts.[15] Using assumptions on the moisture content of pulpwood receipts (as harvested, 50 percent), paper, and paperboard (3 percent), wood pulp consumed (10 percent), and recovered paper consumed (15 percent), Dr. Peter Ince of USDA-FS developed the following relationship:

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[12] EPA. 2006. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004*. U.S. Environmental Protection Agency, Office of Air and Radiation, Washington, DC. EPA- 430-R-06-002.
[13] AF&PA. 2005. *Wood pulp, recovered paper, pulpwood 25th Annual survey, 2004-2007*. Washington, DC.
[14] AF&PA, 2004. *2004 Statistics—Paper, paperboard and wood pulp*. Washington, DC.
[15] FRA, 2004. *Annual pulpwood statistics summary report, 1999-2003*. Rockville, MD.

$$PWH = X \times (PP - [PR \times \{1 - EX\} \times Y]) \qquad \text{(Eqn. 2)}$$

Where,

PWH = pulpwood harvests at 0 percent moisture content, i.e., ovendry (tons)
PP = paper production at 3 percent moisture content (tons)
PR = paper recovery at 15 percent moisture content (tons)
EX = percent of recovered paper that is exported (%)
X = process efficiency of converting ovendry pulpwood to paper and paperboard at 3 percent moisture content. It is the ratio of finished paper to pulp, and accounts for the portion of paper and paperboard that is water and fillers
Y = process efficiency of converting recovered paper at 15 moisture to paper and paperboard at 3 percent moisture. It is the ratio of recovered paper to finished paper, and accounts for the water in recovered paper.

The values of X and Y are based on process yield estimates provided by John Klungness (Research Chemical Engineer, USDA-FS) and Ken Skog (Project Leader, Timber Demand and Technology Assessment Research, USDA-FS). The value for EX, the export rate, is based on examining total paper recovery and exports over the last 10 years for which data were available (1995-2004). Given that our focus is on the effect of small changes in paper recovery, it is more appropriate to focus on the marginal ratio of exports to paper recovery (rather than the average ratio). Thus, EPA calculated the change in annual exports for the end of the period compared to the beginning (3.23 million tons) and divided this figure by the change in annual paper recovery for the end of the period compared to the beginning (8.1 million tons), yielding a value of 40 percent. EPA used 40 percent as the export rate for both types of paper (mechanical and chemical).

As shown in Exhibit 3-4, the avoided pulpwood harvest is 0.58 tons per ton paper recovered for mechanical pulp papers, and 0.89 tons per ton paper recovered for chemical pulp papers.

Exhibit 3-4
Relationship Between Paper Recovery and Pulpwood Harvest (Values of Eqn. 2 Parameters)

	a Ratio of Pulp to Finished Paper	b (= 1 / a) X = Process Efficiency	c Y = Ratio of Recovered Paper to Finished Paper	d EX	e (= b × c × [1 − d]) Avoided Tons PWH per Ton Paper Recovered
Mechanical Pulp	0.900	1.11	0.875	40%	0.58
Chemical Pulp	0.475	2.11	0.700	40%	0.89

3.5.2 The Effect of Change in Pulpwood Harvest on Forest Carbon—FORCARB II Analysis

FORCARB II simulates the complex, dynamic nature of forest systems, including the interaction of various forest carbon pools, how carbon stocks in those pools change over time, and whether the response of forest carbon is linearly proportional to harvests. To explore these questions, USDA-FS ran two enhanced recycling/reduced pulpwood harvest scenarios in FORCARB II. The base assumptions on pulpwood harvests are derived from NAPAP (North American Pulp and Paper) Model baseline projections developed for the Forest Service 2001 RPA Timber Assessment. The two reduced harvest scenarios involved decreasing pulpwood harvest by 6.7 million tons and 20.2 million tons for the period 2005-2009. Harvests in all other periods were the same as the baseline.

For each scenario, EPA calculated the delta in carbon stocks with respect to the base case—this represents the carbon benefit of reduced harvests associated with recycling. The change in carbon was divided by the incremental tons of pulpwood harvested to yield results in units of MTCE per metric ton pulpwood not harvested, i.e., the carbon storage rate.

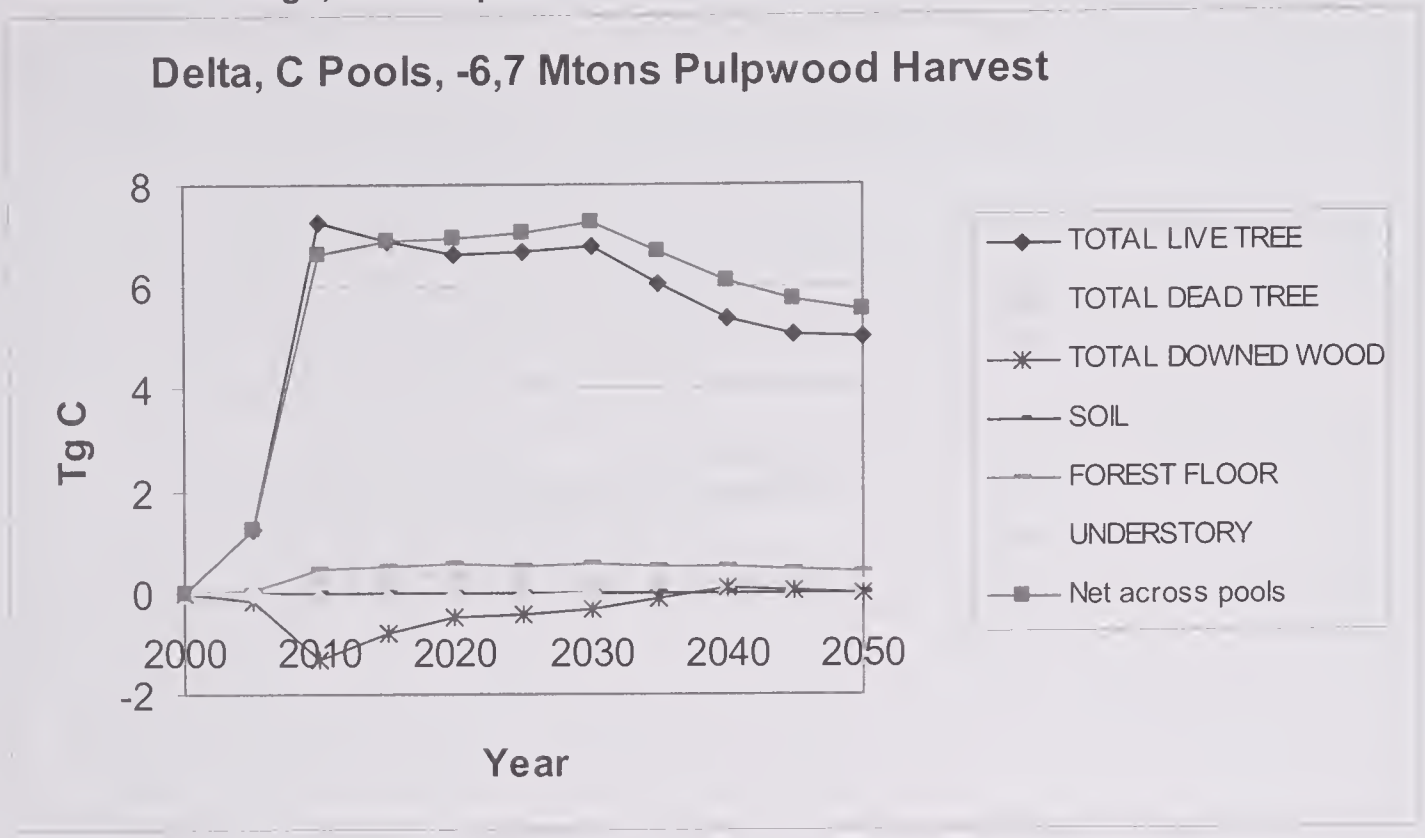
As shown in Exhibit 3-5, the carbon storage rate starts at about 0.99 MTCE per metric ton pulpwood in 2010, increases to about 1.08 MTCE per metric ton pulpwood in 2030, and declines with time to about 0.82 MTCE Carbon per metric ton pulpwood in 2050. The exhibit also shows that across the two incremental recovery scenarios, the carbon storage rate (per unit paper recovered) was virtually identical.

Exhibit 3-5 Increased Forest Carbon Storage per Unit of Reduced Pulpwood Harvest

The use of the FORCARB II model allowed analysis of the timing and magnitude of changes in specific carbon pools within the forest. As shown in Exhibit 3-6, the primary effect of reduced pulpwood harvests was to increase the total live tree pool. This effect was offset to some degree by a decrease in the total downed wood pool. Carbon in the total dead tree, forest floor, and understory pools increased slightly; there was no effect on the soil pool. Most of the deltas peaked in 2010 and moderated somewhat over the next 40 years, though forest floor has more of a lag; the delta peaked in 2030. Both of those pools responded quickly to the change in harvests (which occurred for the 2005-2009 period). It appears that the major driver of the net carbon storage estimate is the time it took for the competing effects in the live tree and total downed wood pools to decline back to the baseline levels; since the total downed wood pool returns to baseline levels more quickly than the Live Tree pool, the net actually increased through 2030.

The FORCARB II results indicate that the effect of paper recycling on carbon storage appears to be persistent (i.e., lasting at least for several decades). EPA chose to use the value for 2020 for use in the emission factors, viz., 1.04 MTCE per metric ton pulpwood. The choice of 2020 represents a delay of about 5 to 15 years with respect to the onset of incremental recycling, long enough to reflect the effects of the recycling program, but lower than the peak effect in 2030. As shown above, the effect is relatively stable over time, so the choice of year does not have a significant effect.

Exhibit 3-6 Change, with respect to baseline, in carbon stocks for FORCARB II pools



For additional details on this methodology and a comparison of the FORCARB II results to those from other analyses, please see the *Background Document on the Effect of Paper Recycling on Forest Carbon.*[16]

3.5.3 Effect of Change in Paper Recovery on Forest Carbon

To estimate the rate of forest carbon change per ton of paper recovery, one can multiply the rate of pulpwood harvest (PWH) per ton of paper recovery (PRC) by the rate of forest carbon (FC) change per ton of pulpwood harvest, as shown below:

For mechanical pulp,

0.58 metric ton PWH per metric ton PRC × 1.04 metric ton FC/metric ton PWH = 0.61 metric ton FC/metric ton PRC

For chemical pulp,

0.89 metric ton PWH per metric ton PRC × 1.04 metric ton FC/metric ton PWH = 0.92 metric ton FC/metric ton PRC

Converting to rates of metric tones forest carbon per short ton of paper (to be consistent with units used throughout this report), the values are 0.55 metric ton FC/ton PRC and 0.83 metric ton FC/ton PRC for mechanical and chemical pulps, respectively. The various paper grades fall into mechanical or chemical pulp categories as follows:

- Mechanical pulp papers—newsprint, telephone books, magazines/third class mail
- Chemical pulp papers—office paper, corrugated cardboard, textbooks

[16] Available at the EPA, Global Warming—Waste, "Solid Waste Management and Greenhouse Gases" website. Op cit.

3.5.4 Effect of Source Reduction on Carbon Stocks

EPA estimated source reduction values under two assumptions: that source reduction displaces only virgin inputs, and that it displaces the current mix of virgin and recycled inputs.[17] For the first assumption, 100 percent virgin inputs, EPA used the process efficiency (X) values described in Section 3.5.1 to calculate the amount of pulpwood harvest reduced per ton of paper source reduction. Those values are 1.11 metric ton PWH per metric ton and 2.11 metric ton PWH per metric ton for mechanical and chemical pulps, respectively (as shown in Exhibit 3-4). Multiplying these values by the rate of forest carbon storage per ton of reduced PWH (1.04 MTCE per ton PWH), and converting to short tons, source reduction of mechanical pulp papers manufactured from 100 percent virgin pulp would increase forest carbon storage by 1.04 MTCE per ton, and for chemical pulp papers, 1.98 MTCE per ton. These values are shown in column (d) of Exhibit 3-7.

The second scenario involves the assumption that source reduction would affect production using the current mix of virgin and recycled inputs. Given that displacing recycled inputs would not influence forest carbon per se, in this scenario the forest carbon effect is only attributable to the proportion of inputs that comprise virgin pulp, as shown in column (e) of Exhibit 3-7. The values in column (f) show the result of multiplying the virgin proportion in the current mix by the forest carbon benefit per ton of 100 percent virgin inputs.

Exhibit 3-7 Forest Carbon Storage from Recycling and Source Reduction

(a)	(b)	(c)	(d)	(e)	(f) (f = d × e)
Material	Mechanical (M) or Chemical (C)	Recycling, (MTCE/ton)	Source Reduction, 100% Virgin Inputs (MTCE/ton)	Percent Virgin Inputs in the Current Mix of Inputs	Source Reduction, Current Mix (MTCE/ton)
Corrugated Cardboard	C	0.83	1.98	65.1%	1.29
Magazines/Third-class Mail	M	0.55	1.04	95.9%	1.00
Newspaper	M	0.55	1.04	77.0%	0.80
Office Paper	C	0.83	1.98	95.9%	1.90
Phonebooks	M	0.55	1.04	100.0%	1.04
Textbooks	C	0.83	1.98	95.9%	1.90

[17] Source reduction may conceivably displace 100 percent virgin inputs if the quantity of paper recovered does not change with source reduction, and all recovered paper is used to make new paper. In that case, if the quantity of paper manufactured is reduced through source reduction, all of the reduction in inputs would come from virgin inputs. It is more likely, however, that source reduction reduces both virgin and recycled inputs. In fact, because source reduction would result in less used product being available to recover, it may have a greater effect on recovered fiber use than on virgin fiber. Thus, even the current mix scenario may represent the high end of the range of effects on forest carbon storage.

3.5.5 Limitations and Uncertainties of the Forest Carbon Analysis

There are several limitations associated with the analysis. The forest product market is very complex, and EPA's simulation of some of the underlying economic relationships that affect the market simplifies some important interactions.

As noted earlier, the results are very sensitive to the assumption on paper exports (i.e., that paper exports comprise a constant proportion of total paper recovery). If all of the recovered paper is exported, none of the incremental recovery results in a corresponding reduction in U.S. pulpwood harvest. At the other extreme, if all of the incremental recovery results in a corresponding reduction in U.S. pulpwood harvest, the storage factor would be higher. The results are also sensitive to assumptions on the moisture content and the carbon content of pulpwood, pulp, and paper.

Also, this analysis does not consider the effect that decreases in pulpwood harvest may have on the supply curve for sawtimber, which could result in a potential increase in harvests of other wood products. This could result in a smaller reduction in harvest, offsetting some of the carbon storage benefit estimated here. Prestamon and Wear[18] investigated how pulpwood and sawtimber supply would change with changes in prices for each. They estimated that non-industrial private forest and industry may increase sawtimber supply when price for pulpwood increases—and the change is perceived as temporary—although the estimate was not statistically significant. But the sawtimber supply may decrease when pulpwood price increases—and the change is perceived as permanent—but once again the estimate was not statistically significant. Given that the relationship between the price change for pulpwood and supply of sawtimber was not consistent and was often statistically insignificant, there was not compelling evidence to indicate that the omission of this effect is a significant limitation to the analysis.

A related issue is that if there is a decrease in the domestic harvest of pulpwood, it could result in a decrease in the cost of domestic production, which could shift the balance between domestic paper production and imports to meet demand.

Another limitation of the analysis is that it did not account for any potential long-term changes in land use due to a reduction in pulpwood demand, and landowners' choices to change land use from silviculture to other uses. If overall forest area is reduced, this would result in significant loss of carbon stocks. Hardie and Parks[19] developed an area base model for use in Resource Planning Act assessments to help determine factors that influence land area change. They derived a model that estimated the elasticity of forest land area change with respect to pulpwood price change. They estimated the elasticity to be -0.10 but this was not significant at the 10 percent confidence level. This suggests that forest area change would be limited with a modest price change in pulpwood demand.

In summary, there are several limitations and uncertainties associated with the analysis, but they are generally less significant compared to the uncertainty associated with the question of how much paper is exported. Despite the limitations and uncertainties, this analysis provides a reasonable approximation of the effects that increased paper recovery would have on forest carbon stocks.

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[18] J.P. Prestamon and D.N. Wear. 2000. *Linking Harvest Choices to Timber Supply.* Forest Science 46 (3): 377-389.

[19] I.W. Hardie and P.J. Parks. 1997. *Land Use with Heterogeneous Land Quality: An Application of an Area Base Model.* American Journal of Agricultural Economics 79:299-310.

3.6 LIMITATIONS

Because the data presented in this chapter were developed earlier in Chapter 2, the limitations discussed in those chapters also apply to the values presented here. Other limitations are as follows:

- There may be GHG impacts from disposal of industrial wastes, particularly paper sludge at paper mills. Because of the complexity of analyzing these second-order effects and the lack of data, EPA did not include them. A screening analysis for paper sludge was performed based on (1) data on sludge generation rates and sludge composition (i.e., percentage of cellulose, hemicellulose, lignin, etc. in sludge),[20] and (2) professional judgment on the CH_4 generation rates for cellulose, etc. The screening analysis indicated that net GHG emissions (CH_4 emissions minus carbon storage) from paper sludge are probably on the order of 0.00 MTCE per ton of paper made from virgin inputs to 0.01 MTCE per ton for recycled inputs. The worst case bounding assumptions indicated maximum possible net GHG emissions ranging from 0.03 to 0.11 MTCE per ton of paper (depending on the type of paper and whether virgin or recycled inputs are used).

- The recycling results are reported in terms of GHG emissions per ton of material collected for recycling. Thus, the emission factors incorporate assumptions on loss of material through collection, sorting, and remanufacturing. There is uncertainty in the loss rates: some materials recovery facilities and manufacturing processes may recover or use recycled materials more or less efficiently than estimated here.

- The models used to evaluate forest carbon sequestration and those used to evaluate energy and nonenergy emissions differ in their methods for accounting for loss rates. Although one can directly adjust the emission factors reported here for process emissions so that they apply to tons of materials as marketed (rather than tons as collected), there is no straightforward way to adjust the forest carbon estimate.

- Because the modeling approach assumes closed-loop recycling for all materials except mixed paper, it does not fully reflect the prevalence and diversity of open-loop recycling. Most of the materials in the analysis are recycled into a variety of manufactured products, not just into the original material. Resource limitations prevent an exhaustive analysis of all the recycling possibilities for each of the materials analyzed.

- For the purpose of simplicity, EPA assumed that increased recycling does not change overall demand for products. In other words, it was assumed that each incremental ton of recycled inputs would displace virgin inputs in the manufacturing sector. In reality, there may be a relationship between recycling and demand for products with recycled content, since these products become cheaper as the supply of recycled materials increases.

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[20] ICF Consulting. 1996. Memorandum to EPA Office of Solid Waste, "Methane Generation from Paper Sludge," December.

Exhibit 3-8
GHG Emissions for Recycling (MTCE/Ton of Material Recovered)

(a) Material	(b) Recycled Input Credit[a]: Process Energy	(c) Recycled Input Credit[a]: Transportation Energy	(d) Recycled Input Credit[a]: Process Nonenergy	(e) Forest Carbon Sequestration	(f) (f = b + c + d + e) GHG Reductions From Using Recycled Inputs Instead of Virgin Inputs
Aluminum Cans	-2.92	-0.12	-0.66	0.00	-3.70
Steel Cans	-0.48	-0.01	0.00	0.00	-0.49
Copper Wire	-1.33	-0.02	0.00	0.00	-1.34
Glass	-0.03	0.00	-0.04	0.00	-0.08
HDPE	-0.34	0.00	-0.04	0.00	-0.38
LDPE	-0.42	0.00	-0.04	0.00	-0.46
PET	-0.40	0.00	-0.02	0.00	-0.42
Corrugated Cardboard	0.00	-0.01	0.00	-0.83	-0.85
Magazines/Third-class Mail	0.00	0.00	0.00	-0.83	-0.84
Newspaper	-0.20	-0.01	0.00	-0.55	-0.76
Office Paper	0.06	0.00	0.00	-0.83	-0.78
Phonebooks	-0.17	0.00	0.00	-0.55	-0.72
Textbooks	-0.01	0.00	0.00	-0.83	-0.85
Dimensional Lumber	0.02	0.00	0.00	-0.69	-0.67
Medium-density Fiberboard	0.01	0.00	0.00	-0.69	-0.67
Mixed Paper					
Broad Definition	-0.10	-0.03	0.00	-0.83	-0.96
Residential Definition	-0.10	-0.03	0.00	-0.83	-0.96
Office Paper Definition	-0.08	-0.02	0.00	-0.83	-0.93
Carpet	-1.47	-0.02	-0.47	0.00	-1.96
Personal Computers	-0.41	-0.01	-0.20	0.00	-0.62
Clay Bricks	NA	NA	NA	NA	NA
Concrete	0.00	0.00	0.00	0.00	0.00
Fly Ash	-0.11	0.00	-0.12	0.00	-0.24
Tires[b]	-1.75	0.00	0.00	0.00	-1.75

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

[a] Material that is recycled after use is then substituted for virgin inputs in the production of new products. This credit represents the difference in emissions that results from using recycled inputs rather than virgin inputs. The credit accounts for loss rates in collection, processing, and remanufacturing. Recycling credit is based on closed- and open-loop recycling depending on material.

[b] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

Explanatory notes for Exhibit 3-8

Columns "b" and "c" show the reduction in process energy GHGs and transportation energy GHGs from making each material from recycled inputs, rather than virgin inputs. The values in columns "b" and "c" are based on (1) the difference in energy-related GHG emissions between making 1 ton of the material from 100 percent virgin inputs and from 100 percent recycled inputs, multiplied by (2) the estimated tons of material manufactured from 1 ton of material recovered, after accounting for loss rates in the recovery and remanufacturing stages. EPA first estimated the values in columns "b" and "c" based on provided by FAL and ORD, as shown in Exhibits 2-3 through 2-6. Note that for two of the mixed paper definitions, the process energy GHG emissions are higher when using recycled inputs than when using virgin inputs (as shown by positive values in column "b"). This difference is because the manufacture of boxboard (the product of open-loop recycling of these types of mixed paper) from virgin inputs uses a high proportion of biomass fuels, and the biogenic CO_2 emissions from biomass fuels are not counted as GHG emissions (see the discussion of biogenic CO_2 emissions in Chapter 1). Still, because of forest carbon sequestration, the net GHG emissions from recycling these two mixed paper definitions are negative.

For column "d, " which presents the process nonenergy GHG emissions from recycling, EPA used (1) data showing the difference in process nonenergy GHG emissions between making 1 ton of the material from 100 percent virgin inputs and from 100 percent recycled inputs (as shown in the second-to-last column of Exhibits 2-3 and 2-5) multiplied by (2) the estimated amount of material manufactured (in tons) from 1 ton of material recovered, after accounting for loss rates in the recovery and remanufacturing steps.

Next, column "e" shows the estimated forest carbon sequestration from recycling of paper products, as estimated in Section 3.5 The last column (column "f") sums columns "b" through "e" to show the GHG implications of recycling each material.

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4. COMPOSTING

This chapter presents estimates of GHG emissions and sinks from composting yard trimmings and food discards (henceforth, organics).[1] It examines only emissions and sinks from centralized (e.g. municipal) composting, rather than from backyard composting or other localized composting operations. The chapter is organized as follows:

Section 4.1 presents an estimate of potential anthropogenic GHG emissions from composting;

Section 4.2 quantifies the potential carbon storage benefits of applying compost to soils;

Section 4.3 presents net GHG emissions from composting; and

Section 4.4 discusses the limitations of this analysis.

Composting may result in (1) CH_4 emissions from anaerobic decomposition; (2) long-term carbon storage in the form of undecomposed carbon compounds; and (3) nonbiogenic CO_2 emissions from collection and transportation of the organic materials to the central composting site, and from mechanical turning of the compost pile.[2] Composting also results in biogenic CO_2 emissions associated with decomposition, both during the composting process and after the compost is added to the soil. Because this CO_2 is biogenic in origin, however, it is not counted as a GHG in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*[3] (as explained in Section 1.4.2) and is not included in this accounting of emissions and sinks.

Research suggests that composting, when managed properly, does not generate CH_4 emissions, but it does result in some carbon storage (associated with application of compost to soils), as well as minimal CO_2 emissions from transportation and mechanical turning of the compost piles. In order to maintain consistency with other chapters in this report, EPA selected point estimates from the range of emission factors—covering various compost application rates and time periods—developed in the analysis. The point estimates were chosen based on a "typical" compost application rate of 20 tons of compost per acre, averaged over three soil-crop scenarios. The carbon storage values for the year 2010 were selected to be consistent with the time between onset of the program and carbon storage effect as simulated in the forest carbon storage estimates presented in Chapter 3 of this report. Overall, EPA estimates that centralized composting of organics results in net GHG storage of 0.05 MTCE/wet ton of organic inputs composted and applied to agricultural soil.

4.1 POTENTIAL GHG EMISSIONS

Two potential types of GHG emissions are associated with composting: (1) CH_4 from anaerobic decomposition, and (2) nonbiogenic CO_2 from transportation of compostable materials and turning of the compost piles.

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[1] Although paper and mixed MSW can be composted, EPA did not analyze the GHG implications of composting them because of time and resource constraints.

[2] CO_2 emissions from delivery of compost to its final destination were not counted because compost is a marketable product, and CO_2 emissions from transportation of other marketable, finished goods to consumers have not been counted in other parts of this analysis.

[3] EPA. 2005. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC. EPA 430-R-05-003.

4.1.1 CH_4

To research the issue of CH_4 emissions, EPA first conducted a literature search for articles on CH_4 generation from composting. Because CH_4 emissions from composting are addressed only occasionally in the literature, EPA contacted several composting experts from universities and USDA to discuss the potential for CH_4 generation, based on the nature of carbon flows during composting. The CH_4 analysis presented here is based on their expert opinions.

The researchers EPA contacted stated that well-managed compost operations usually do not generate CH_4 because they typically maintain an aerobic environment with proper moisture content to encourage aerobic decomposition of the materials. The researchers also noted that even if CH_4 is generated in anaerobic pockets in the center of the compost pile, the CH_4 is most likely oxidized when it reaches the oxygen-rich surface of the pile, where it is converted to CO_2. Several of the researchers commented that anaerobic pockets are most apt to develop when too much water is added to the compost pile. They noted that this problem rarely occurs because compost piles are much more likely to be watered too little rather than too much.

EPA concluded from the available information that CH_4 generation from centralized compost piles is essentially zero.

4.1.2 CO_2 from Transportation of Materials and Turning of Compost

This study estimated the indirect CO_2 emissions associated with collecting and transporting organics to centralized compost facilities, and turning the compost piles. EPA began with estimates developed by FAL for the amount of diesel fuel required to (1) collect and transport 1 ton of organics[4] to a central composting facility (363,000 Btu) and (2) turn the compost pile (221,000 Btu).[5] EPA then converted these estimates to units of MTCE per ton of organics, based on a carbon coefficient of 0.02 MTCE per million Btu of diesel fuel. This resulted in an estimate of 0.01 MTCE of indirect CO_2 emissions per ton of material composted in a centralized facility.

4.2 POTENTIAL CARBON STORAGE

EPA also evaluated the effect of compost application on soil carbon storage. Information on carbon storage associated with compost derived specifically from yard trimmings or food discards was not found. Nevertheless, it is reasonable to expect that these materials have similar fates in terms of their stored carbon, even though their initial moisture and carbon contents differ.

To develop carbon storage estimates for composted organics, EPA researched the processes that affect soil carbon storage, reviewed the results of experiments on the soil carbon impacts of applying organic amendments (e.g., compost, manure, biosolids, and crop residues), and interviewed experts on the potential carbon storage benefits of composting organics as compared to other methods of disposal. During this process, four hypotheses were proposed regarding the benefits of applying organics compost to soil:

(1) Many soils have been depleted in organic matter through cultivation and other practices. Adding compost can raise soil carbon levels by increasing organic matter inputs. Soils degraded by intensive crop production, construction, mining, and other activities lose organic matter when decomposition rates and removals of carbon in harvests exceed the rate of new inputs of organic materials. Adding compost shifts the balance so that soil organic carbon levels are restored to higher levels. Some of the compost carbon is retained by the system.

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[4] Measured on a wet weight basis, as MSW is typically measured.

[5] Franklin Associates, Ltd. 1994. *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (Stamford, CT: Keep America Beautiful), pp. I-27, 30, and 31.

(2) Nitrogen in compost can stimulate higher productivity, thus generating more crop residues. This "fertilization effect" would increase soil carbon due to the larger volume of crop residues, which serve as organic matter inputs.

(3) The composting process leads to increased formation of stable carbon compounds (e.g., humic substances, aggregates) that then can be stored in the soil for long (>50 years) periods of time. Humic substances make up 60–80 percent of soil organic matter and are made up of complex compounds that render them resistant to microbial attack.[6] In addition to humic substances, soil organic carbon may be held in aggregates (i.e., stable organo-mineral complexes in which carbon is bonded with clay colloids and metallic elements) and protected against microbial attack.[7]

(4) The application of compost produces a multiplier effect by qualitatively changing the dynamics of the carbon cycling system and increasing the retention of carbon from noncompost sources. Some studies of other compost feedstocks (e.g., farmyard manure, legumes) have indicated that the addition of organic matter to soil plots can increase the potential for storage of soil organic carbon. The carbon increase apparently comes not only from the organic matter directly, but also from retention of a higher proportion of carbon from residues of crops grown on the soil. This multiplier effect could enable compost to increase carbon storage by more than its own direct contribution to carbon mass accumulation.

EPA's research efforts did not yield any primary data that could be used to develop quantitative estimates of the soil carbon storage benefits of compost. Therefore, modeling approaches to investigate the possible effects of compost application on soil carbon storage were developed. Section 4.2.2 describes application of the CENTURY model to quantify soil carbon restoration and nitrogen fertilization associated with compost application to carbon-depleted soils. EPA conducted a bounding analysis, described in Section 4.2.6, to address the third hypothesis, incremental humus formation. Although several of the experts contacted cited persuasive qualitative evidence of the existence of a multiplier effect, EPA was unable to develop an approach to quantify this process. In that sense, the carbon storage estimates are likely to be conservative (i.e., understate carbon storage rates), at least for soils with high silt and/or clay content where this process is most likely to apply.

EPA's analyses of soil carbon restoration, nitrogen fertilization, and incremental humus formation apply relatively simple models of very complex processes. These processes probably are controlled by a number of biological, physicochemical, and compost management factors, such as application (i.e., silviculture, horticulture, agriculture, and landscaping); application rate; regional and local climatic factors; soil type; and, to a lesser extent, compost feedstock (e.g., grass, leaves, branches, yard trimmings, food discards). In addition, the results are time-dependent, so the year in which benefits are assessed has an effect on the magnitude of carbon storage.

Note that the framework used here describes the soil carbon benefits of composting relative to landfilling and combustion. In all three management methods, yard trimmings are collected and removed from soils in residential or commercial settings. This removal may result in some loss of organic carbon from the "home soil." An estimate of the "absolute" soil carbon storage value would net out whatever loss occurs due to the removal of the yard trimmings. This effect is probably a negligible one, however, and EPA was unable to find empirical data on it. Because the decrement in carbon in "home soil" applies equally to all three management practices, and emission factors are intended to be viewed relative to other management practices (see Chapter 8), neglecting the carbon loss from the home soil does not compromise the validity of the results.

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[6] N. Brady and R. Weil. 1999. *The Nature and Properties of Soils* (Upper Saddle River, NJ: Prentice Hall).
[7] R. Lal et al. 1998. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor, MI: Sleeping Bear Press, Inc).

4.2.1 Modeling Soil Carbon Restoration and Nitrogen Fertilization

As mentioned above, this analysis included an extensive literature review and interviews with experts to consider whether the application of compost leads to long-term storage of carbon in soils. After determining that neither the literature review nor discussions with experts would yield a basis for a quantitative estimate of soil carbon storage, EPA evaluated the feasibility of a simulation modeling approach. EPA initially identified two simulation models with the potential to be applied to the issue of soil carbon storage from compost application: CENTURY[8] and the Rothamsted C (ROTHC-26.3)[9] model. Both are peer-reviewed models whose structure and application have been described in scores of publications. They share several features:

- Ability to run multiyear simulations;
- Capability to construct multiple scenarios covering various climate and soil conditions and loading rates; and
- Ability to handle interaction of several soil processes, environmental factors, and management scenarios such as carbon: nitrogen (C:N) ratios, aggregate formation, soil texture (e.g., clay content), and cropping regime.

Given the extensive application of CENTURY in the United States, its availability on the Internet, and its ability to address many of the processes important to compost application, it was decided to use CENTURY rather than ROTHC-26.3.

4.2.2 CENTURY Model Framework

CENTURY is a Fortran model of plant-soil ecosystems that simulates long-term dynamics of carbon, nitrogen, phosphorus, and sulfur. It tracks the movement of carbon through soil pools—active, slow, and passive—and can show changes in carbon levels due to the addition of compost.

In addition to soil organic matter pools, carbon can be found in surface (microbial) pools and in above- and below-ground litter pools. The above-ground and below-ground litter pools are divided into metabolic and structural pools based on the ratio of lignin to nitrogen in the litter. The structural pools contain all of the lignin and have much slower decay rates than the metabolic pools. Carbon additions to the system flow through the various pools and can exit the system (e.g., as CO_2, dissolved carbon, or through crop removals).

The above-ground and below-ground litter pools are split into metabolic and structural pools based on the ratio of lignin to nitrogen in the litter. The structural pools contain all of the lignin and have much slower decay rates than the metabolic pools. The active pool of soil organic matter includes living biomass, some of the fine particulate detritus,[10] most of the nonhumic material, and some of the more easily decomposed fulvic acids. The active pool is estimated to have a mean residence time (MRT)[11] of a few months to 10 years.[12] The slow pool includes resistant plant material (i.e., high lignin content) derived from the structural pool and other slowly decomposable and chemically resistant components. It has an MRT of 15–100 years.[13] The passive pool of soil organic matter includes very stable materials remaining in the soil for hundreds to thousands of years.[14]

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[8] Metherell, A., L. Harding, C. Cole, W. Parton. 1993. CENTURY Agroecosystem Version 4.0, Great Plains System Research Unit Technical Report No. 4, USDA-ARS Global Climate Change Research Program (Colorado State University: Fort Collins, CO).

[9] This model was developed based on long-term observations of soil carbon at Rothamsted, an estate in the United Kingdom where organic amendments have been added to soils since the 19th century.

[10] Detritus refers to debris from dead plants and animals.

[11] The term "mean residence time" is used interchangeably with "turnover time" and is the average time in which a unit (e.g., a carbon atom) resides within a "state" where there is both an input and an output. MRT is only strictly defined at steady-state (i.e., inputs = outputs), but as most soils systems have a continuing input of carbon and an

CENTURY does not simulate increased formation of humic substances associated with organic matter additions, nor does it allow for organic matter additions with high humus content to increase the magnitude of the passive pool directly. (Because CENTURY does not account for these processes, EPA developed a separate analysis, described in Section 4.2.6.)

CENTURY contains a submodel to simulate soil organic matter pools. Additional submodels address nitrogen, phosphorus, sulfur, the water budget, leaching, soil temperature, and plant production, as well as individual submodels for various ecosystems (e.g., grassland, cropland). The nitrogen submodel addresses inputs of fertilizer and other sources of nitrogen, mineralization of organic nitrogen, and uptake of nitrogen by plants.

4.2.3 Inputs

The CENTURY model simulates the long-term dynamics of various plant-soil ecosystems (e.g., grassland, agricultural land, forest, and savanna). The model uses a series of input files to specify modeling conditions: crop, harvest, fertilization, cultivation, organic matter addition, irrigation, grazing, fire, tree type, tree removal, site, and weather statistics. A schedule file is used to specify the timing of events.

For this analysis, EPA developed a basic agricultural scenario where land was converted from prairie to farmland (growing corn) in 1921 and remains growing corn through 2030. More than 30 scenarios were then run to examine the effect of several variables on soil carbon storage:

- Compost application rate and frequency;
- Site characteristics (rainfall, soil type, irrigation regime);
- Fertilization rate; and
- Crop residue management.

Compost application rates were adjusted using the organic matter (compost) files for each compost application rate included in the analysis. EPA compared the effect of applying compost annually for 10 years (1996–2005) at seven different application rates: 1.3, 3.2, 6.5, 10, 15, 20, and 40 wet tons compost/acre (corresponding to 60–1,850 grams of carbon per square meter).[15] EPA also investigated the effect of compost application frequency on the soil carbon storage rate and total carbon levels. The model was run to simulate compost applications of 1.3 wet tons compost/acre and 3.2 wet tons compost/acre every year for 10 years (1996–2005) and applications of 1.3 wet tons compost/acre and 3.2 wet tons compost/acre applied every five years (in 1996, 2001, and 2006). The simulated

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approximately equal output through decomposition and transfer to other pools, MRT is often used to describe carbon dynamics in soils. Mathematically, it is the ratio of (a) mass in the pool to (b) throughput of carbon. For example, if a given carbon pool has a mass of 1,000 kg and the inflow is 1 kg/yr, the MRT is 1,000 kg / (1 kg/yr) = 1,000 yr.

[12] Metherell et al. 1993, Brady and Weil 1999.

[13] *Ibid.*

[14] *Ibid.*

[15] The model requires inputs in terms of the carbon application rate in grams per square meter. The relationship between the carbon application rate and compost application rate depends on three factors: the moisture content of compost, the organic matter content (as a fraction of dry weight), and the carbon content (as a fraction of organic matter). Inputs are based on values provided by Dr. Harold Keener of Ohio State University, who estimates that compost has a moisture content of 50 percent, an organic matter fraction (as dry weight) of 88 percent, and a carbon content of 48 percent (as a fraction of organic matter). Thus, on a wet weight basis, 21 percent of compost is carbon.

compost was specified as having 33 percent lignin,[16] 17:1 C:N ratio,[17] 60:1 carbon-to-phosphorus ratio, and 75:1 carbon-to-sulfur ratio.[18] EPA also ran a scenario with no compost application for each combination of site-fertilization-crop residue management. This scenario allowed EPA to control for compost application, i.e., to calculate the change in carbon storage attributable only to the addition of compost.

The majority of inputs needed to specify a scenario reside in the site file. The input variables in this file include the following:

- Monthly average maximum and minimum air temperature;
- Monthly precipitation;
- Lignin content of plant material;
- Plant nitrogen, phosphorus, and sulfur content;
- Soil texture;
- Atmospheric and soil nitrogen inputs; and
- Initial soil carbon, nitrogen, phosphorus, and sulfur levels.

Several sets of detailed site characteristics from past modeling applications are available to users. EPA chose two settings: an eastern Colorado site with clay loam soil and a southwestern Iowa site with silty clay loam soil. Both settings represent fairly typical Midwestern corn belt situations where agricultural activities have depleted soil organic carbon levels. The Colorado scenario is available as a site file on the CENTURY Web site.[19] Dr. Keith Paustian, an expert in the development and application of CENTURY, provided the specifications for the Iowa site (as well as other input specifications and results for several of the runs described here).

EPA also varied the fertilization rate. As discussed earlier, one of the hypotheses was that the mineralization of nitrogen in compost could stimulate crop growth, leading to production of more organic residues, which in turn would increase soil organic carbon levels. The strength of this effect would vary depending on the availability of other sources of nitrogen (N). To investigate this hypothesis, different rates of synthetic fertilizer addition ranging from zero up to a typical rate to attain average crop yield—90 pounds (lbs.) N/acre for the Colorado site, 124 lbs. N/per acre for the Iowa site—were analyzed. EPA also evaluated fertilizer application at half of these typical rates.

Finally, two harvest regimes were simulated, one where the corn is harvested for silage (where 95 percent of the above-ground biomass is removed) and the other where corn is harvested for grain (where the "stover" is left behind to decompose on the field). These simulations enabled EPA to isolate the

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[16] Percent lignin was estimated based on the lignin fractions for grass, leaves, and branches specified by compost experts (particularly Dr. Gregory Evanylo at Virginia Polytechnic Institute and State University, and lignin fractions reported in M.A. Barlaz, "Biodegradative Analysis of Municipal Solid Waste in Laboratory-Scale Landfills," EPA 600/R-97-071, 1997. FAL provided an estimate of the fraction of grass, leaves, and branches in yard trimmings in a personal communication with ICF Consulting, November 14, 1995. Subsequently, FAL obtained and provided data showing that the composition of yard trimmings varies widely in different states. The percentage composition used here (50 percent grass, 25 percent leaves, and 25 percent branches on a wet weight basis) is within the reported range.

[17] The C:N ratio was taken from Brady and Weil, 1999, *The Nature and Property of Soils: Twelfth Edition* (Upper Saddle River, NJ: Prentice Hall).

[18] C:P and C:S ratios were based on the literature and conversations with composting experts, including Dr. Gregory Evanylo at Virginia Polytechnic Institute and State University.

[19] The Natural Resource Ecology Laboratory at Colorado State University, CENTURY Soil Organic Matter Model, Version 5.0, available at: http://www.nrel.colostate.edu/projects/century5

effect of the carbon added directly to the system in the form of compost, as opposed to total carbon inputs (which include crop residues).

4.2.4 Outputs

CENTURY is capable of providing a variety of output data, including carbon storage in soils, CO_2 emissions due to microbial respiration, and monthly potential evapotranspiration. The outputs EPA chose were carbon levels for each of the eight soil pools: structural carbon in surface litter, metabolic carbon in surface litter, structural carbon in soil litter, metabolic carbon in soil litter, surface pool, active pool, slow pool, and passive pool. The output data cover the period from 1900 through 2030. In general, EPA focused on the difference in carbon storage between a baseline scenario, where no compost was applied, and a with-compost scenario. EPA calculated the difference between the two scenarios to isolate the effect of compost application. Output data in grams of carbon per square meter were converted to MTCE by multiplying by area (in square meters).

To express results in units comparable to those for other sources and sinks, EPA divided the increase in carbon storage by the short tons of organics required to produce the compost.[20] That is, the factors are expressed as a carbon storage rate in units of MTCE per wet short ton of organic inputs (not MTCE per short ton of compost).

4.2.5 Results

The carbon storage rate declines with time after initial application. The rate is similar across application rates and frequencies, and across the site conditions that were simulated. Exhibit 4-1 displays results for the Colorado and Iowa sites, for the 10-, 20-, and 40-ton per acre application rates. As indicated on the graph, the soil carbon storage rate varies from about 0.08 MTCE per wet ton organics immediately after compost application (in 1997) to about 0.02 MTCE per ton in 2030 (24 years after the last application in 2006).

The similarity across the various site conditions and application rates reflects the fact that the dominant process controlling carbon retention is the decomposition of organic materials in the various pools. As simulated by CENTURY, this process is governed by first-order kinetics, i.e., the rate is independent of organic matter concentration or the rate of organic matter additions.

Several secondary effects, however, result in some variation in the carbon storage rate.[21] EPA had hypothesized that where a crop's demand for nitrogen exceeds its availability from other sources, mineralization of compost nitrogen can stimulate increased productivity. Simulation of this effect showed that where there is a shortage of nitrogen, compost application can result in higher productivity, which translates into higher inputs of crop residues to the soil. These higher inputs in turn increase the carbon storage rate per unit of compost inputs. This effect is a relatively modest one, however.

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[20] EPA assumes 2.1 tons of yard trimmings are required to generate 1 ton of composted yard trimmings. Thus, to convert the results in this report (in MTCE per wet ton yard trimmings) to MTCE per wet ton of compost, multiply by 2.1. To convert to MTCE per dry ton compost, multiply values in this report by 4.2 (assuming 50 percent moisture content).

[21] In addition to the nitrogen fertilization effect, compost also affects moisture retention in soils, which in turn modifies the water balance relations simulated by CENTURY.

Exhibit 4-1
Soil Carbon Storage--Colorado and Iowa sites; 10, 20, and 40 tons-per-acre Application Rates

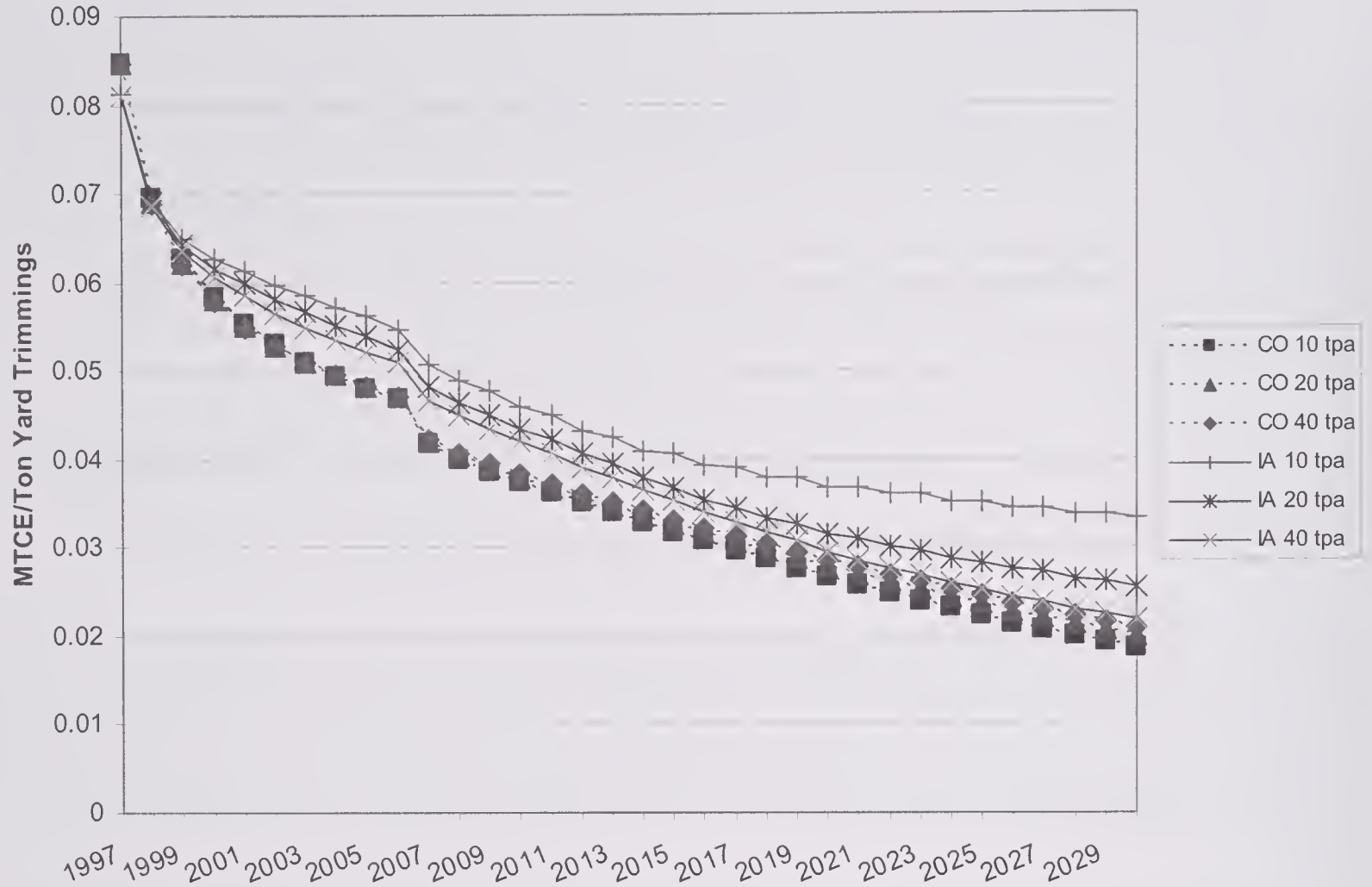
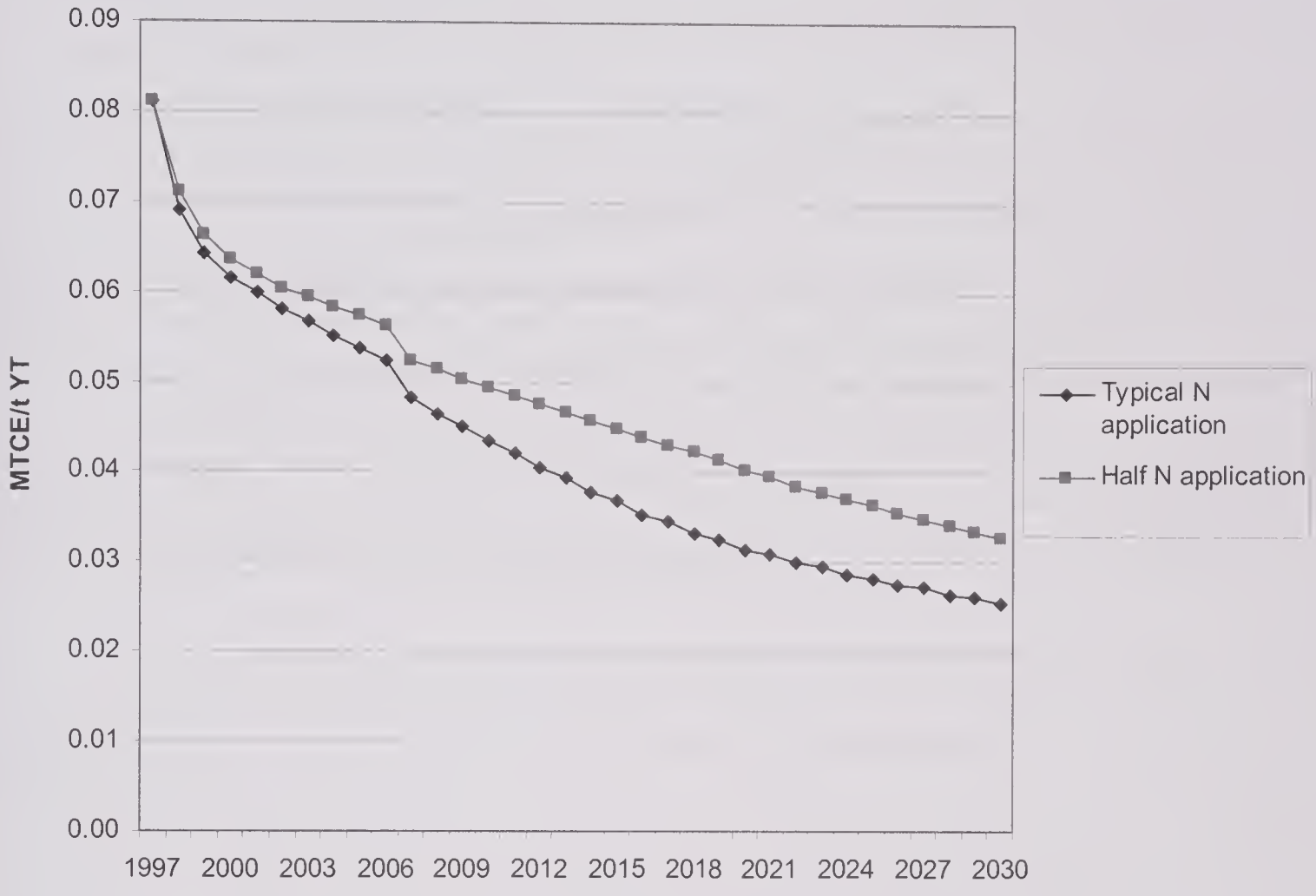


Exhibit 4-2 shows the carbon storage rate for the Iowa site and the effect of nitrogen fertilization. The two curves in the exhibit both represent the difference in carbon storage between (a) a with-compost scenario (20 tons per acre) and (b) a baseline where compost is not applied. The nitrogen application rates differ in the following ways:

- The curve labeled "Typical N application" represents application of 124 lbs. per acre, for both the compost and baseline scenario. Because the nitrogen added via compost has little effect when nitrogen is already in abundant supply, this curve portrays a situation where the carbon storage is attributable solely to the organic matter additions in the compost.
- The curve labeled "Half N application" represents application of 62 lbs. per acre. In this scenario, mineralization of nitrogen added by the compost has an incremental effect on crop productivity compared to the baseline. The difference between the baseline and compost application runs reflects both organic matter added by the compost and additional biomass produced in response to the nitrogen contributed by the compost.

The difference in incremental carbon storage rates between the two fertilization scenarios is less than 0.01 MTCE per ton, indicating that the nitrogen fertilization effect is small. Note that this finding is based on the assumption that farmers applying compost also will apply sufficient synthetic fertilizer to maintain economic crop yields. If this assumption is not well-founded, or in situations where compost is applied as a soil amendment for road construction, landfill cover, or similar situations, the effect would be larger.

Exhibit 4-2 Incremental Carbon Storage as a Function of Nitrogen Application Rate



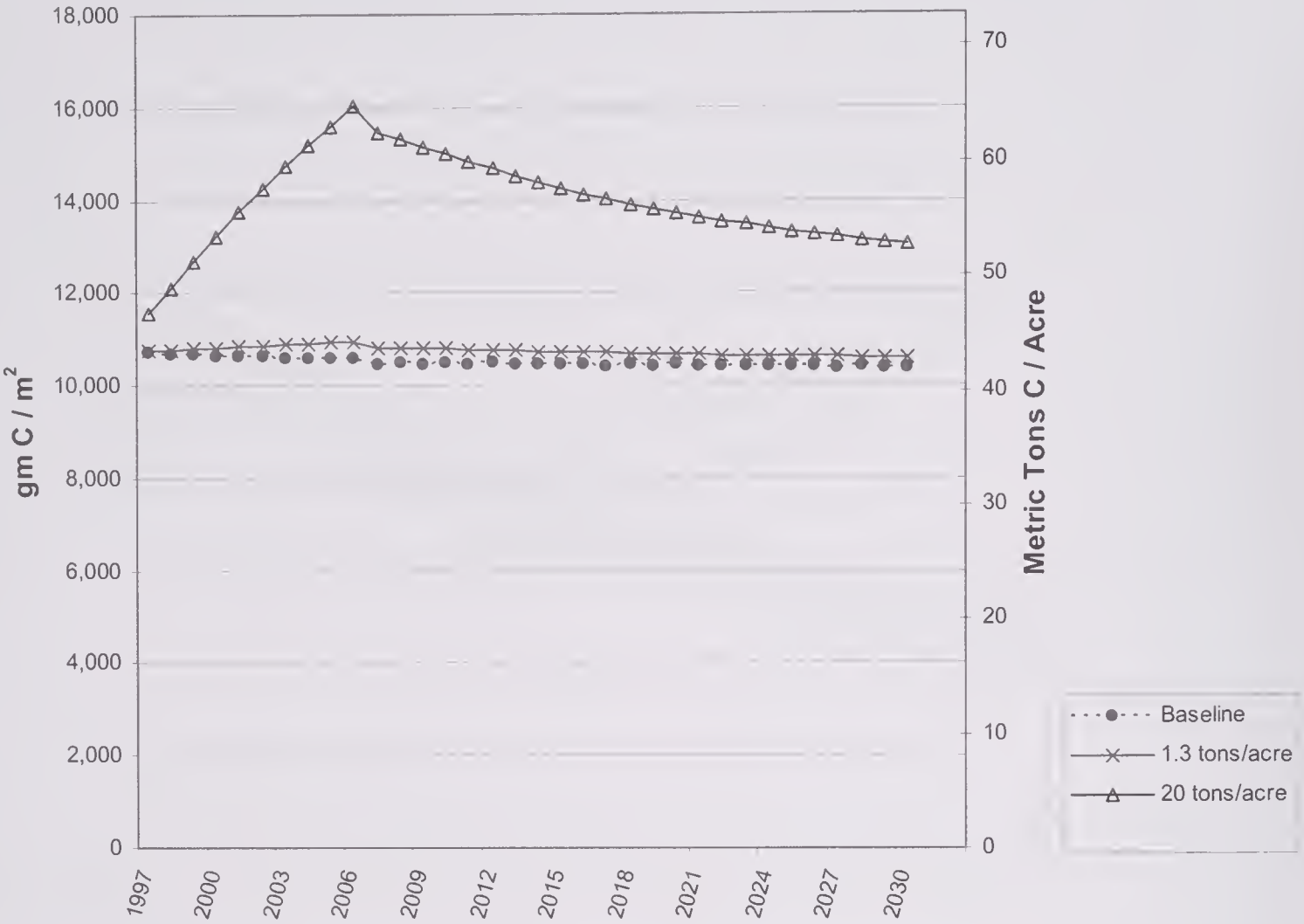
When viewed from the perspective of total carbon, rather than as a storage rate per ton of inputs to the composting process, both soil organic carbon concentrations and total carbon stored per acre increase with increasing application rates (see Exhibit 4-3). Soil organic carbon concentrations increase throughout the period of compost application, peak in 2006 (the last year of application), and decline thereafter due to decomposition of the imported carbon. Exhibit 4-3 displays total carbon storage (including baseline carbon) in soils on the order of 40 to 65 metric tons per acre (the range would be higher with higher compost application rates or longer term applications).

4.2.6 Incremental Humus Formation

The third of the four hypotheses describing the benefits of composting, as compared to alternative management methods, is predicated on incremental formation of stable carbon compounds that can be stored in the soil for long periods of time. CENTURY does not simulate this process, i.e., it does not allow for organic matter additions with high humus content to directly increase the magnitude of the passive pool. Therefore, EPA used a bounding analysis to estimate the upper and lower limits of the magnitude of this effect. In this analysis, EPA evaluated the amount of long-term soil carbon storage when organics are composted and applied to soil.

During the process of decomposition, organic materials typically go through a series of steps before finally being converted to CO_2, water, and other reaction products. The intermediate compounds that are formed, and the lifetime of these compounds, can vary widely depending on a number of factors, including the chemical composition of the parent compound. Parent compounds range from readily degradable molecules such as cellulose and hemicellulose to molecules more resistant to degradation, such as lignin, waxes, and tannins.

Exhibit 4-3 Total Soil C; Iowa Site, Corn Harvested for Grain



Composting is designed to promote rapid decomposition of organics, thus reducing their volume. Some evidence suggests that composting produces a greater proportion of humus than that typically formed when organics are left directly on the ground. The conditions in the two phases are different. The heat generated within compost piles favors "thermophilic" (heat-loving) bacteria, which tend to produce a greater proportion of stable, long-chain carbon compounds (e.g., humic substances) than do bacteria and fungi that predominate at ambient soil temperatures.

Increased humus formation associated with compost application is a function of two principal factors:

(1) The fraction of carbon in compost that is considered "passive" (i.e., very stable); and

(2) The rate at which passive carbon is degraded to CO_2.

Estimates for the first factor are based on experimental data compiled by Dr. Michael Cole of the University of Illinois. Dr. Cole found literature values indicating that between 4 and 20 percent of the carbon in finished compost degrades quickly.[22] Dr. Cole averaged the values he found in the literature and estimated that 10 percent of the carbon in compost can be considered "fast" (i.e., readily degradable). The remaining 90 percent can be classified as either slow or passive. EPA was unable to locate experimental data that delineate the fractions of slow and passive carbon in compost; therefore, upper and lower bound estimates based on Dr. Cole's professional judgment were developed. He suggested values

[22] Very little information is available on the characteristics of compost derived from yard trimmings or food discards. However, Dr. Cole found that the composition of composts derived from other materials is broadly consistent, suggesting that his estimates may be reasonably applied to yard trimmings or food scrap compost.

of 30 percent slow and 60 percent passive, and 45 percent slow and 45 percent passive for the upper and lower bounds on passive content, respectively.[23]

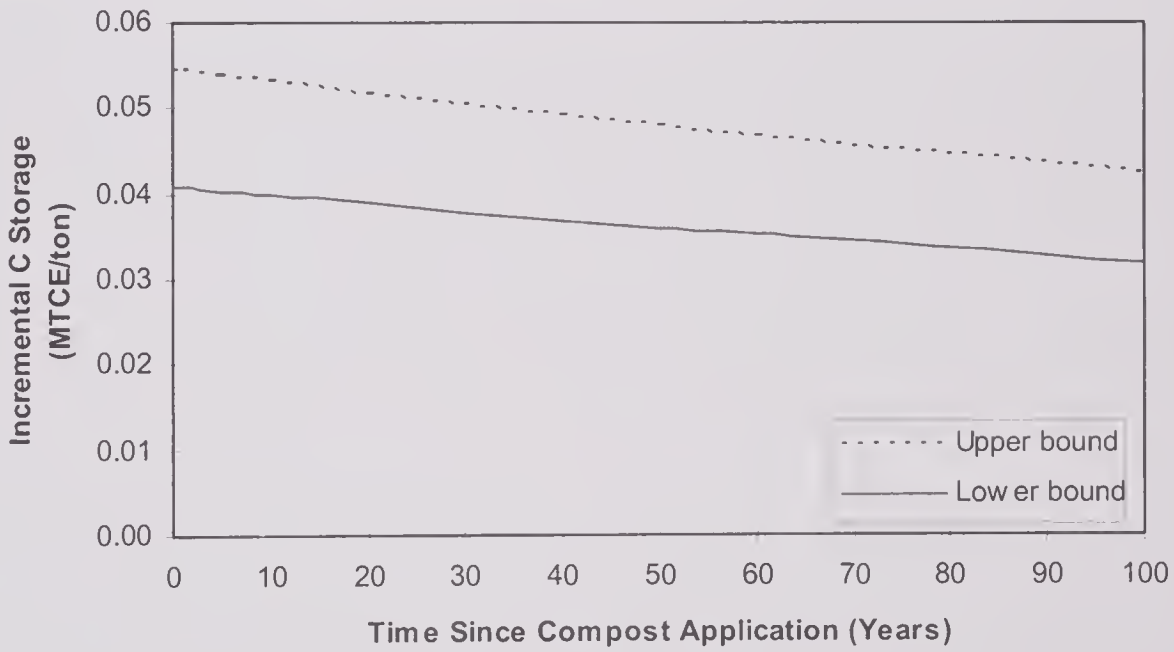
For the second factor, EPA chose a mean residence time for passive carbon of 400 years based on the range of values specified in the literature.[24]

Combining the two bounds for incremental humus formation (60 percent passive and 45 percent passive), EPA estimated the incremental carbon storage implied by each scenario (see Exhibit 4-4).

The upper bound on the incremental carbon storage from composting is more than 0.05 MTCE per wet ton of organics (shown in the top left of the graph); the lower bound is approximately 0.03 MTCE per wet ton (shown in the bottom right of the graph) after about 100 years. Incremental storage is sensitive to the fraction of carbon in compost that is passive but is not very sensitive to the degradation rate (within a 100-year time horizon, over the range of rate constants appropriate for passive carbon).

To select a point estimate for the effect of incremental humus formation, EPA took the average storage value across the two bounding scenarios, when time equals 10 years (i.e., approximately 2010). The resulting value is 0.046 MTCE/ton. The 2010 time frame was chosen for this analysis because the forest carbon estimates presented in Chapter 3 of this report are for the period ending in 2010.

Exhibit 4-4 Incremental Carbon Storage: MTCE/Wet Ton Versus Time



[23] EPA focused only on the passive pool because (1) the CENTURY model does not allow for direct input of organic carbon into the passive pool, and (2) the model runs resulted in very little indirect (i.e., via other pools) formation of passive carbon. Although the first factor is also true for the slow pool, the second is not. Had EPA analyzed slow carbon in the same way as passive carbon, there would be potential for double counting (see discussion in Section 4.3).

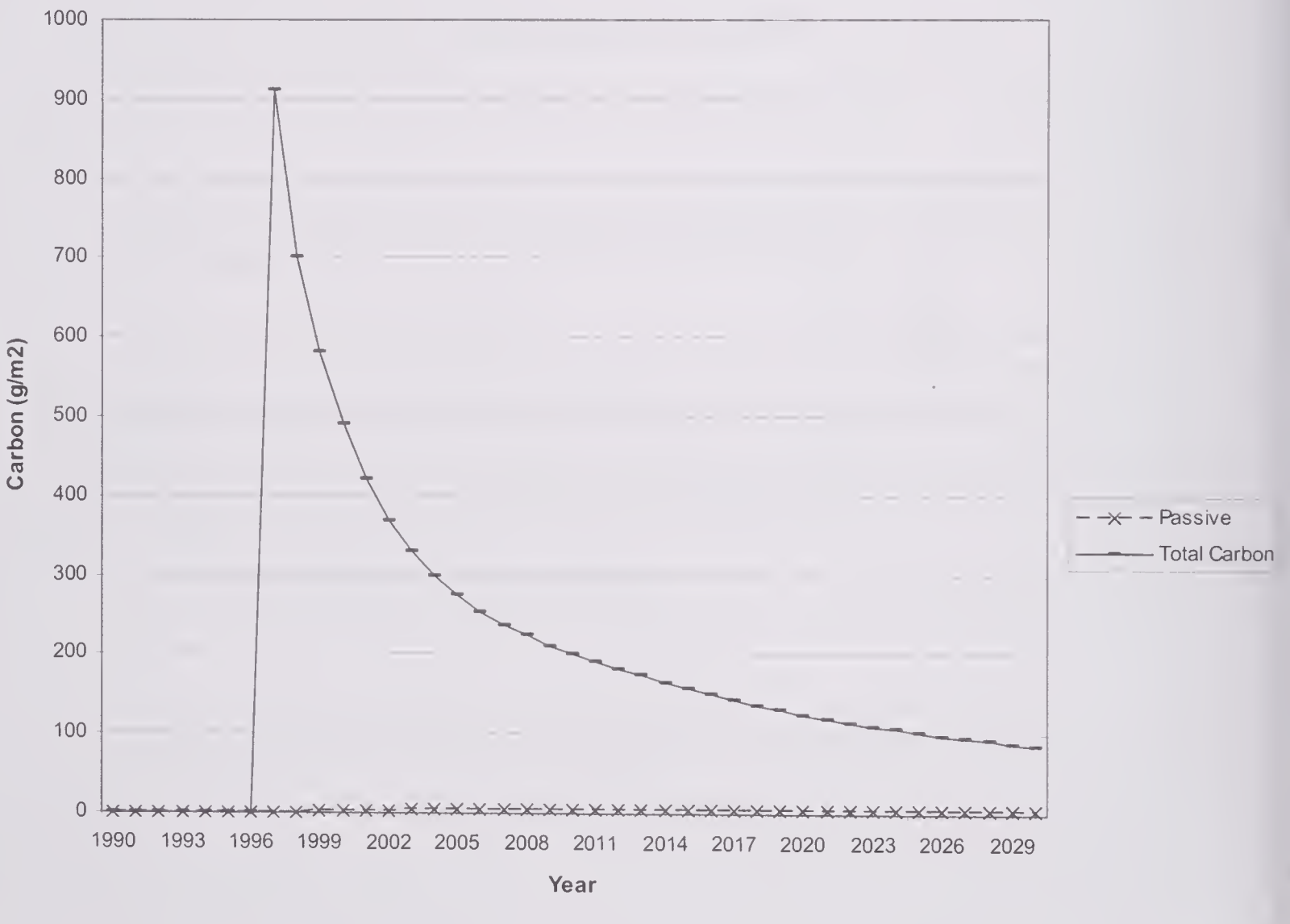
[24] Metherell et al. 1993, Brady and Weil 1999.

4.3 NET GHG EMISSIONS FROM COMPOSTING

The approaches described in Section 4.2 were adopted to capture the range of carbon storage benefits associated with compost application. However, this dual approach creates the possibility of double counting. In an effort to eliminate double counting, EPA evaluated the way that CENTURY partitions compost carbon once it is applied to the soil.

To do so, EPA ran a CENTURY model simulation of compost addition during a single year and compared the results to a corresponding reference case (without compost). EPA calculated the difference in carbon in each of the CENTURY pools for the two simulations and found that the change in the passive pool represented less than 0.01 percent of the change in total carbon. Therefore, CENTURY is not adding recalcitrant carbon directly to the passive pool. Next, EPA graphed the change in the passive pool over time to ensure that the recalcitrant compost carbon was not being cycled from the faster pools into the passive pool several years after the compost is applied. As Exhibit 4-5 shows, CENTURY does not introduce significant increments (over the base case) of recalcitrant carbon into the passive pool at any time.

Exhibit 4-5 Difference in Carbon Storage Between Compost Addition and Base Case Yearly Application with 20 Tons Compost



Based on the analysis, it appears that CENTURY is appropriately simulating carbon cycling and storage for all but the passive carbon introduced by compost application. Because passive carbon represents approximately 52 percent of carbon in compost (the midpoint of 45 percent and 60 percent), EPA scaled the CENTURY results by 48 percent to reflect the proportion of carbon that can be classified as fast or slow (i.e., not passive).

Exhibit 4-6 shows the soil carbon storage and transportation-related emissions and sinks, and sums these to derive estimates of a net GHG emission factor, using the same sign convention as the broader analysis. A negative value denotes carbon storage; a positive value denotes emissions.

Summing the values corresponding to typical application rate and the 2010 time frame for soil carbon restoration (-0.02 MTCE/ton), increased humus formation (-0.05 MTCE/ton), and transportation emissions (0.01 MTCE/ton), the result is –0.05 MTCE/ton.[25]

Exhibit 4-6
Net GHG Emissions from Composting
(In MTCE Per Ton of Yard Trimmings Composted)

Emission/ Storage Factor (for 2010)					
Soil Carbon Restoration			Increased Humus Formation	Transportation Emissions	Net Carbon Flux
Unweighted	Proportion of C that is Not Passive	Weighted Estimate			
-0.04	48%	-0.02	-0.05	0.01	-0.05

4.4 LIMITATIONS

Due to data and resource constraints, this chapter does not explore the full range of conditions under which compost is managed and applied, and how these conditions would affect the results of this analysis. Instead, this study attempts to provide an analysis of GHG emissions and sinks associated with centralized composting of organics under a limited set of scenarios. EPA's analysis was limited by the lack of primary research on carbon storage and CH_4 generation associated with composting. The limited availability of data forced EPA to rely on two modeling approaches, each with its own set of limitations. In addition, the analysis was limited by the scope of the report, which is intended to present life-cycle GHG emissions of waste management practices for selected material types, including food discards and yard trimmings.

4.4.1 Limitations of Modeling Approaches

Due to data and resource constraints, EPA was unable to use CENTURY to evaluate the variation in carbon storage impacts for a wide range of compost feedstocks (e.g., yard trimmings mixed with food discards, food discards alone). As noted earlier, resource constraints limited the number of soil types, climates, and compost applications simulated. The CENTURY results also incorporate the limitations of the model itself, which have been well documented elsewhere. Perhaps most importantly, the model's predictions of soil organic matter levels are driven by four variables: annual precipitation, temperature, soil texture, and plant lignin content. Beyond these, the model is limited by its sensitivity to several factors for which data are difficult or impossible to obtain (e.g., presettlement grazing intensity, nitrogen input during soil development).[26] The model's monthly simulation intervals limit its ability to fully address potential interactions between nitrogen supply, plant growth, soil moisture, and decomposition rates, which may be sensitive to conditions that vary on a shorter time scale.[27] In addition, the model is not designed to capture the hypothesis that, due to compost application, soil ecosystem dynamics change so that more carbon is stored than is actually being added to the soil (i.e., the multiplier effect).

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[25] The addends do not sum to the total, due to rounding.
[26] Parton, W., D. Schimel, C. Cole, and D. Ojima. 1987. "Analysis of Factors Controlling Soil Organic Matter Levels in Great Plains Grasslands." *Soil Sci. Soc. Am. J.* Vol. 51 (1173-1179).
[27] Paustian, K., W. Parton, and Jan Persson. 1992. "Modeling Soil Organic Matter in Organic-Amended and Nitrogen-Fertilized Long-Term Plots." *Soil Sci. Soc. Am. J.* Vol. 56 (476-488).

CENTURY simulates carbon movement through organic matter pools. Although the model is designed to evaluate additions of organic matter in general, it is not believed to have been applied in the past to evaluate the application of organics compost. CENTURY is parameterized to partition carbon to the various pools based on ratios of lignin to nitrogen and lignin to total carbon, not on the amount of organic material that has been converted to humus already. EPA addressed this limitation by developing an "add-on" analysis to evaluate humus formation in the passive pool, scaling the CENTURY results, and summing the soil carbon storage values. There is some potential for double counting, to the extent that CENTURY is routing some carbon to various pools that is also accounted for in the incremental humus analysis. EPA believes that this effect is likely to be minor.

The bounding analysis used to analyze increased humus formation is limited by the lack of data specifically dealing with composts composed of yard trimmings or food discards. This analysis is also limited by the lack of data on carbon in compost that is passive. The approach of taking the average value from the two scenarios is simplistic but appears to be the best available option.

4.4.2 Limitations Related to the Scope of the Report

As indicated above, this chapter presents EPA's estimates of the GHG-related impacts of composting organics. These estimates were developed within the framework of the larger report; therefore, the presentation of results, estimation of emissions and sinks, and description of ancillary benefits is not comprehensive. The remainder of this section describes specific limitations of the compost analysis.

As in the other chapters of this report, the GHG impacts of composting reported in this chapter are relative to other possible disposal options for yard trimmings (i.e., landfilling and combustion). In order to present absolute GHG emission factors for composted yard trimmings that could be used to compare composting to a baseline of leaving yard trimmings on the ground where they fall, EPA would need to analyze the home soil. In particular, the carbon storage benefits of composting would need to be compared to the impact of removal of yard trimmings on the home soil.

As mentioned in Section 4.4.1, due to data and resource constraints, the analysis considers a small sampling of feedstocks and a single compost application (i.e., agricultural soil). EPA analyzed two types of compost feedstocks—yard trimmings and food discards—although sewage sludge, animal manure, and several other compost feedstocks also may have significant GHG implications. Similarly, it was assumed that compost was applied to degraded agricultural soils, despite widespread use of compost in land reclamation, silviculture, horticulture, and landscaping.

This analysis did not consider the full range of soil conservation and management practices that could be used in combination with compost and the impacts of those practices on carbon storage. Some research indicates that adding compost to agricultural soils in conjunction with various conservation practices enhances the generation of soil organic matter to a much greater degree than applying compost alone. Examples of these conservation practices include conservation tillage, no tillage, residue management, crop rotation, wintering, and summer fallow elimination. Research suggests that allowing crop residues to remain on the soil rather than turning them over helps to protect and sustain the soil while simultaneously enriching it. Alternatively, conventional tillage techniques accelerate soil erosion, increase soil aeration, and hence lead to greater GHG emissions.[28] Compost use also has been shown to increase soil water retention; moister soil gives a number of ancillary benefits, including reduced irrigation costs and reduced energy used for pumping water. Compost can also play an important role in the adaptation strategies that will be necessary as climate zones shift with climate change and some areas become more arid.

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[28] R. Lal et al. 1998. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor, MI: Sleeping Bear Press, Inc).

As is the case in other chapters, the methodology used to estimate GHG emissions from composting did not allow for variations in transportation distances. EPA recognizes that the density of landfills versus composting sites in any given area would have an effect on the extent of transportation emissions derived from composting. For example, in states that have a higher density of composting sites, the hauling distance to such a site would be less and would require less fuel than transportation to a landfill. Alternatively, transporting compost from urban areas, where compost feedstocks may be collected, to farmlands, where compost is typically applied, potentially would require more fuel because of the large distance separating the sites.

Emission factors presented in this chapter do not capture the full range of possible GHG emissions from compost. Some of the nitrogen in compost is volatilized and released into the atmosphere as N_2O shortly after application of the compost. Based on a screening analysis, N_2O emissions were estimated to be less than 0.01 MTCE per wet ton of compost inputs.

Addressing the possible GHG emission reductions and other environmental benefits achievable by applying compost instead of chemical fertilizers, fungicides, and pesticides was beyond the scope of this report. Manufacturing those agricultural products requires energy. To the extent that compost may replace or reduce the need for these substances, composting may result in reduced energy-related GHG emissions. Although EPA understands that compost is generally applied for its soil amendment properties rather than for pest control, compost has been effective in reducing the need for harmful or toxic pesticides and fungicides.[29]

In addition to the carbon storage benefits of adding compost to agricultural soils, composting can lead to improved soil quality, improved productivity, and cost savings. As discussed earlier, nutrients in compost tend to foster soil fertility.[30] In fact, composts have been used to establish plant growth on land previously unable to support vegetation. In addition to these biological improvements, compost also may lead to cost savings associated with avoided waste disposal, particularly for feedstocks such as sewage sludge and animal manure.

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[29] For example, the use of compost may reduce or eliminate the need for soil fumigation with methyl bromide (an ozone-depleting substance) to kill plant pests and pathogens.

[30] N. Brady and R. Weil. 1999.

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5. COMBUSTION

This chapter presents estimates of the net GHG emissions from combustion of most of the materials considered in this analysis and several categories of mixed waste streams (e.g., mixed paper, mixed recyclables, and mixed MSW). Combustion of MSW results in emissions of CO_2 (because nearly all of the carbon in MSW is converted to CO_2 under optimal conditions) and N_2O. Note that CO_2 from burning biomass sources (such as paper products and yard trimmings) is not counted as a GHG because it is biogenic (as explained in Section 1.4.2).

Combustion of MSW with energy recovery in a waste-to-energy (WTE) plant also results in *avoided* CO_2 emissions at utility and metals production facilities. First, the electricity produced by a WTE plant displaces electricity that would otherwise be provided by an electric utility power plant. Because most utility power plants burn fossil fuels and thus emit CO_2, the electricity produced by a WTE plant reduces utility CO_2 emissions. These avoided GHG emissions are subtracted from the GHG emissions associated with combustion of MSW. Second, most MSW combusted with energy recovery in the United States is combusted in WTE plants that recover ferrous metals (e.g., steel) and nonferrous materials (e.g., nonferrous metals and glass).[1] The recovered ferrous metals and nonferrous materials then are recycled. As discussed in Chapter 4, processes using recycled inputs require less energy than processes using virgin inputs. In measuring GHG implications of combustion, one also must account for the change in energy use due to recycling associated with metals recovery.

WTE facilities can be divided into three categories: (1) mass burn, (2) modular, or (3) refuse-derived fuel (RDF). A mass burn facility generates electricity and/or steam from the combustion of mixed MSW. In the United States, about 65 mass burn facilities process approximately 22 million tons of MSW annually.[2] Modular WTE plants generally are smaller than mass burn plants and are prefabricated off-site so that they can be assembled quickly where they are needed. Because of their similarity to mass burn facilities, modular facilities are treated as part of the mass burn category for the purposes of this analysis.

An RDF facility combusts MSW that has undergone varying degrees of processing, from simple removal of bulky and noncombustible items to more complex processes (shredding and material recovery) that result in a finely divided fuel. Processing MSW into RDF yields a more uniform fuel that has a higher heating value than is produced by mass burn or modular WTE.[3] In the United States, approximately 10 facilities process and combust RDF, 5 facilities combust RDF using off-site processing, and 5 facilities process RDF for combustion off-site. These RDF facilities process approximately 8 million tons of MSW annually.[4]

This study analyzed the net GHG emissions from combustion of mixed waste streams and the following individual materials at mass burn and RDF facilities:

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[1] EPA did not consider any recovery of materials from the MSW stream that may occur before MSW is delivered to the combustor. EPA considered such prior recovery to be unrelated to the combustion operation—unlike recovery of steel from combustor ash, an activity that is an integral part of the operation of many combustors.

[2] Integrated Waste Services Association, *The 2004 IWSA Waste-To-Energy Directory of United States Facilities*, Table 1.

[3] MSW processing into RDF involves both manual and mechanical separation to remove materials such as glass and metals that have little or no fuel value.

[4] Integrated Waste Services Association, *The 2004 IWSA Waste-To-Energy Directory of United States Facilities*, Table 1.

- Aluminum Cans;
- Steel Cans;
- Copper Wire;
- Glass;
- HDPE Plastic;
- LDPE Plastic;
- PET Plastic;
- Corrugated Cardboard;
- Magazines and Third-class Mail;
- Newspaper;
- Office Paper;
- Phonebooks;[5]
- Textbooks;[6]
- Dimensional Lumber;
- Medium-density Fiberboard;
- Food Discards;
- Yard Trimmings;
- Carpet;
- Personal Computers; and
- Tires.

Net emissions consist of (1) emissions of nonbiogenic CO_2 and N_2O minus (2) avoided GHG emissions from the electric utility sector and from processing with recycled inputs (e.g., steel produced from recycled inputs requires less energy than steel from virgin inputs). There is some evidence that as combustor ash ages, it absorbs CO_2 from the atmosphere. However, EP A did not count absorbed CO_2 because the quantity is estimated to be less than 0.01 MTCE per ton of MSW combusted.[7] Similarly, the residual waste from processing MSW into RDF is typically landfilled. Some potential exists for the organic fraction of this residual waste to yield GHG emissions when landfilled. EPA did not count these emissions, however, because the quantity emitted is estimated to be less than 0.01 MTCE per ton of MSW processed into RDF.[8]

The results showed that combustion of mixed MSW has small negative net GHG emissions (in absolute terms). Combustion of paper products, dimensional lumber, medium-density fiberboard, food

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[5] Newspaper used as proxy, as material-specific data were unavailable.
[6] Office paper used as proxy, as material-specific data were unavailable.
[7] Based on data provided by Dr. Jurgen Vehlow, of the Institut für Technische Chemie in Karlsruhe, Germany, EPA estimated that the ash from 1 ton of MSW would absorb roughly 0.004 MTCE of CO_2.
[8] Based on data provided by Karen Harrington, principal planner for the Minnesota Office of Environmental Assistance, EPA estimated that landfilling the residual waste would emit roughly 0.003 MTCE of CO_2 per ton of MSW processed into RDF. Facsimile from Karen Harrington, Minnesota Office of Environmental Assistance to ICF Consulting, October 1997.

discards, yard trimmings, and personal computers results in negative net GHG emissions. Processing steel cans at a combustor, followed by recycling the ferrous metal, likewise results in negative net GHG emissions. Combustion of plastic produces positive net GHG emissions, and combustion of aluminum cans, copper wire, and glass results in small positive net GHG emissions. The reasons for each of these results are discussed in this chapter.[9]

5.1 METHODOLOGY

The study's general approach was to estimate the (1) gross emissions of CO_2 and N_2O from MSW and RDF combustion (including emissions from transportation of waste to the combustor and ash from the combustor to a landfill) and (2) CO_2 emissions avoided due to displaced electric utility generation and decreased energy requirements for production processes using recycled inputs.[10] To obtain an estimate of the *net* GHG emissions from MSW and RDF combustion, the GHG emissions avoided was subtracted from the direct GHG emissions. EPA estimated the net GHG emissions from waste combustion per ton of mixed MSW and per ton of each selected material in MSW. The remainder of this section describes how EPA developed these estimates.

5.1.1 Estimating Direct CO_2 Emissions from MSW Combustion

The carbon in MSW has two distinct origins. Some of it is derived from sustainably harvested biomass (i.e., carbon in plant and animal matter that was converted from CO_2 in the atmosphere through photosynthesis). The remaining carbon in MSW is from nonbiomass sources, e.g., plastic and synthetic rubber derived from petroleum.

For reasons described in Section 1.4.2, EPA did not count the biogenic CO_2 emissions from combustion of biomass. On the other hand, CO_2 emissions from combustion of nonbiomass components of MSW—plastic, textiles, and rubber—were counted. Overall, only a small portion of the total CO_2 emissions from combustion are counted as GHG emissions.

For mixed MSW, EPA used the simplifying assumptions that (1) all carbon in textiles is nonbiomass carbon, i.e., petrochemical-based plastic fibers such as polyester (this is a worst-case assumption); and (2) the category of "rubber and leather" in EPA's MSW characterization report[11] is composed almost entirely of rubber. Based on these assumptions, EPA estimated that there are 0.11 lbs. of nonbiogenic carbon in the plastic, textiles, rubber, and leather contained in one lb. of mixed MSW.[12] EPA assumed that 98 percent of this carbon would be converted to CO_2 when the waste is combusted, with the balance going to the ash. The 0.11 lbs. of nonbiomass carbon per one lb. of mixed MSW then was converted to units of MTCE per ton of mixed MSW combusted. The resulting value for mixed MSW is 0.10 MTCE per ton of mixed MSW combusted,[13] as shown in Exhibit 5-1.

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[9] Note that Exhibit 5-1, Exhibit 5-2, and Exhibit 5-5 do not show mixed paper. Mixed paper is shown in the summary exhibit (Exhibit 5-6). The summary values for mixed paper are based on the proportions of the four paper types (newspaper, office paper, corrugated cardboard, and magazines/third-class mail) that make up the different "mixed paper" definitions.

[10] A comprehensive evaluation also would consider the fate of carbon remaining in combustor ash. Depending on its chemical form, carbon may be aerobically degraded to CO_2, anaerobically degraded to CH_4, or remain in a relatively inert form and be stored. Unless the ash carbon is converted to CH_4 (which EPA considers unlikely), the effect on the net GHG emissions would be very small.

[11] EPA 2005. *Municipal Solid Waste in the United States: 2003 Facts and Figures.* Office of Solid Waste. EPA530-F-05-003.

[12] ICF Consulting. 1995. Memorandum. "Work Assignment 239, Task 2: Carbon Sequestration in Landfills," April 28, Exhibit 2-A, column "o."

[13] Note that if EPA had used a best-case assumption for textiles, i.e., assuming they have no petrochemical-based fibers, the resulting value for mixed MSW would have been 0.09 MTCE per ton of mixed MSW combusted.

EPA estimated that HDPE and LDPE are 84 percent carbon, while PET is 57 percent carbon (based on a moisture content of 2 percent). EPA assumed that 98 percent of the carbon in the plastic is converted to CO_2 during combustion. The values for CO_2 emissions, converted to units of MTCE per ton of plastic combusted, are shown in column "b" of Exhibit 5-1.

5.1.2 Estimating N_2O Emissions from Combustion of Waste

Studies compiled by the IPCC show that MSW combustion results in measurable emissions of N_2O, a GHG with a high GWP.[14] The IPCC compiled reported ranges of N_2O emissions, per metric ton of waste combusted, from six classifications of MSW combustors. This study averaged the midpoints of each range and converted the units to MTCE of N_2O per ton of MSW. The resulting estimate is 0.01 MTCE of N_2O emissions per ton of mixed MSW combusted. Because the IPCC did not report N_2O values for combustion of individual components of MSW, EPA used the 0.01 value not only for mixed MSW, but also as a proxy for all components of MSW, except for aluminum cans, steel cans, glass, HDPE, LDPE, and PET.[15]

5.1.3 Estimating Indirect CO_2 Emissions from Transportation of Waste to the Facility

Next, this study estimated the indirect CO_2 emissions from the transportation of waste. For the indirect CO_2 emissions from transporting waste to the combustion facility, and ash from the combustion facility to a landfill, EPA used an estimate for mixed MSW developed by FAL.[16] EPA then converted the FAL estimate from pounds of CO_2 per ton of mixed MSW to MTCE per ton of mixed MSW. This resulted in an estimate of 0.01 MTCE of CO_2 emissions from transporting 1 ton of mixed MSW and the resulting ash. Transportation of any individual material in MSW was assumed to use the same amount of energy as transportation of mixed MSW.

5.1.4 Estimating Gross GHG Emissions from Combustion

To estimate the gross GHG emissions per ton of waste combusted, EPA summed the values for emissions from combustion CO_2, combustion N_2O, and transportation CO_2. The gross GHG emission estimates, for mixed MSW and for each individual material, are shown in column "e" of Exhibit 5-1.

5.1.5 Estimating Utility CO_2 Emissions Avoided

Most WTE plants in the United States produce electricity. Only a few cogenerate electricity and steam. In this analysis, EPA assumed that the energy recovered with MSW combustion would be in the form of electricity. This analysis is shown in Exhibit 5-2. EPA used three data elements to estimate the avoided electric utility CO_2 emissions associated with combustion of waste in a WTE plant: (1) the energy content of mixed MSW and of each separate waste material considered, (2) the combustion system efficiency in converting energy in MSW to delivered electricity, and (3) the electric utility CO_2 emissions avoided per kilowatt-hour (kWh) of electricity delivered by WTE plants.

Energy content: For the energy content of mixed MSW, EPA used a value of 5,000 Btu per pound of mixed MSW combusted, which is a value commonly used in the WTE industry.[17] This estimate

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[14] U.S. EPA, 2006, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004*, available online at: http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html. The GWP of N_2O is 310 times that of CO_2.

[15] This exception was made because at the relatively low combustion temperatures found in MSW combustors, most of the nitrogen in N_2O emissions is derived from the waste, not from the combustion air. Because aluminum and steel cans, glass, and plastics do not contain nitrogen, EPA concluded that running these materials through an MSW combustor would not result in N_2O emissions.

[16] FAL. 1994. *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (Stamford, CT: Keep America Beautiful, Inc.), p. I-24.

[17] Telephone conversation among representatives of Integrated Waste Services Association, American Ref-Fuel, and ICF Consulting, October 28, 1997.

is within the range of values (4,500 to 6,500 Btu per pound) reported by FAL[18] and is slightly higher than the 4,800 Btu per pound value reported in EPA's *MSW Fact Book*.[19] For the energy content of RDF, a value of 5,700 Btu per pound of RDF combusted was used.[20] This estimate is within the range of values (4,800 to 6,400 Btu per pound) reported by the DOE's National Renewable Energy Laboratory (NREL).[21] For the energy content of specific materials in MSW, EPA consulted three sources: (1) EPA's *MSW Fact Book* (a compilation of data from primary sources), (2) a report by Environment Canada,[22] and (3) a report by Argonne National Laboratories.[23] EPA assumes that the energy contents reported in the first two of these sources were for materials with moisture contents typically found for the materials in MSW (the sources implied this but did not explicitly state it). The Argonne study reported energy content on a dry weight basis.

Combustion system efficiency: To estimate the combustion system efficiency of mass burn plants, EPA used a net value of 550 kWh generated by mass burn plants per ton of mixed MSW combusted.[24]

To estimate the combustion system efficiency of RDF plants, EPA evaluated three sources: (1) data supplied by an RDF processing facility located in Newport, MN; (2) the Integrated Waste Services Association (IWSA) report *Waste-to-Energy Directory: Year 2000*; and (3) the DOE NREL. EPA used the Newport Processing Facility's reported net value of 572 kWh generated per ton of RDF for two reasons.[25] First, this value is within the range of values reported by the other sources. Second, the Newport Processing Facility provided a complete set of data for evaluating the overall system efficiency of RDF plants.[26]

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[18] FAL. 1994. *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (Stamford, CT: Keep America Beautiful, Inc.), pp. 1-16.
[19] EPA, Office of Solid Waste. 1995. *MSW Fact Book, Version 2.0* (Washington, D.C.: U.S. Environmental Protection Agency).
[20] Note that this is a value reported by an RDF facility located in Newport, MN; the data were provided by the Minnesota Office of Environmental Assistance. Facsimile from Karen Harrington, Minnesota Office of Environmental Assistance to ICF Consulting, October 1997.
[21] DOE, National Renewable Energy Laboratory. 1992. *Data Summary of Municipal Solid Waste Management Alternatives Volume IV: Appendix B - RDF Technologies* (Springfield, VA: National Technical Information Service, NREL/TP-431-4988D), p. B-5.
[22] Procter and Redfern, Ltd. and ORTECH International. 1993. *Estimation of the Effects of Various Municipal Waste Management Strategies on Greenhouse Gas Emissions, Part II* (Ottawa, Canada: Environment Canada, Solid Waste Management Division, and Natural Resources Canada, Alternative Energy Division).
[23] Gaines, Linda, and Frank Stodolsky. 1993. *Mandated Recycling Rates: Impacts on Energy Consumption and Municipal Solid Waste Volume* (Argonne, IL: Argonne National Laboratory), pp. 11 and 85.
[24] Note that this is the value reported by Integrated Waste Services Association in its comments to the draft version of the first edition of this report. This value is within the range of values reported by others in response to the draft. Letter received from Maria Zannes, Integrated Waste Services Association, Washington, DC, August 25, 1997.
[25] The net energy value reported accounts for the estimated energy required to process MSW into RDF and the estimated energy consumed by the RDF combustion facility.
[26] The dataset included estimates on the composition and amount of MSW delivered to the processing facility, as well as estimates for the heat value of RDF, the amount of energy required to process MSW into RDF, and the amount of energy used to operate the RDF facility.

Exhibit 5-1
Gross Emissions of GHGs from MSW Combustion (MTCE per Ton Combusted)

(a) Material Combusted	(b) Combustion CO_2 Emissions From Nonbiomass	(c) Combustion N_2O Emissions	(d) Transportation CO_2 Emissions	(e) (e = b + c + d) Gross GHG Emissions
Aluminum Cans	0.00	0.00	0.01	0.01
Steel Cans	0.00	0.00	0.01	0.01
Copper Wire	0.00	0.00	0.01	0.01
Glass	0.00	0.00	0.01	0.01
HDPE	0.76	0.00	0.01	0.77
LDPE	0.76	0.00	0.01	0.77
PET	0.56	0.00	0.01	0.56
Corrugated Cardboard	0.00	0.01	0.01	0.02
Magazines/Third-class Mail	0.00	0.01	0.01	0.02
Newspaper	0.00	0.01	0.01	0.02
Office Paper	0.00	0.01	0.01	0.02
Phonebooks[a]	0.00	0.01	0.01	0.02
Textbooks[a]	0.00	0.01	0.01	0.02
Dimensional Lumber	0.00	0.01	0.01	0.02
Medium-density Fiberboard	0.00	0.01	0.01	0.02
Food Discards	0.00	0.01	0.01	0.02
Yard Trimmings	0.00	0.01	0.01	0.02
Mixed Paper[b]				
Broad Definition	0.00	0.01	0.01	0.02
Residential Definition	0.00	0.01	0.01	0.02
Office Paper Definition	0.00	0.01	0.01	0.02
Mixed MSW	0.10	0.01	0.01	0.12
Carpet	0.47	0.00	0.01	0.48
Personal Computers	0.10	0.00	0.01	0.11
Tires	2.05	0.00	0.01	2.06

Note that totals may not sum due to independent rounding, and more digits may be displayed than are significant.

[a] The values for phonebooks and textbooks are proxies, based on newspaper and office paper, respectively.

[b] The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.

Exhibit 5-2
Avoided Utility GHG Emissions from Combustion at Mass Burn and RDF Facilities

(a) Material Combusted	(b) Energy Content (Btu Per Pound)	(c) Energy Content (Million Btu Per Ton)	(d) Mass Burn Combustion System Efficiency (Percent)	(e) RDF Combustion System Efficiency (Percent)	(f) Emission Factor for Utility-Generated Electricity (MTCE/ Million Btu of Electricity Delivered)	(g) (g = c × d × f) Avoided Utility CO_2 Per Ton Combusted at Mass Burn Facilities (MTCE Per Ton)	(h) (h = c × e × f) Avoided Utility CO_2 Per Ton Combusted at RDF Facilities (MTCE Per Ton)
Aluminum Cans	-335[a]	-0.7	17.8%	16.3%	0.077	-0.01[p]	-0.01[p]
Steel Cans	-210[a]	-0.4	17.8%	16.3%	0.077	-0.01[p]	-0.01[p]
Copper Wire	-273	-0.5	17.8%	16.3%	0.077	-0.01[p]	-0.01[p]
Glass	-235[a]	-0.5	17.8%	16.3%	0.077	-0.01[p]	-0.01[p]
HDPE	18,687[b]	37.4	17.8%	16.3%	0.077	0.52	0.47
LDPE	18,687[b]	37.4	17.8%	16.3%	0.077	0.52	0.47
PET	9,702[c,d]	19.4	17.8%	16.3%	0.077	0.27	0.24
Corrugated Cardboard	7,043[b]	14.1	17.8%	16.3%	0.077	0.19	0.18
Magazines/Third-class Mail	5,258[e]	10.5	17.8%	16.3%	0.077	0.15	0.13
Newspaper	7,950[b]	15.9	17.8%	16.3%	0.077	0.22	0.20
Office Paper	6,800[b,f]	13.6	17.8%	16.3%	0.077	0.19	0.17
Phonebooks	7,950[g]	15.9	17.8%	16.3%	0.077	0.22	0.20
Textbooks	6,800[h]	13.6	17.8%	16.3%	0.077	0.19	0.17
Dimensional Lumber	8,300[i]	16.6	17.8%	16.3%	0.077	0.23	0.21
Medium-density Fiberboard	8,300[i]	16.6	17.8%	16.3%	0.077	0.23	0.21
Food Discards	2,370[b]	4.7	17.8%	16.3%	0.077	0.07	0.06
Yard Trimmings	2,800[j]	5.6	17.8%	16.3%	0.077	0.08	0.07
Mixed Paper							
Broad Definition	7,069	14.1	17.8%	16.3%	0.077	0.20	0.18
Residential Definition	7,039	14.1	17.8%	16.3%	0.077	0.19	0.18
Office Paper Definition	6,499	13.0	17.8%	16.3%	0.077	0.18	0.16
Mixed MSW	5,000[k,l]	10.0	17.8%	16.3%	0.077	0.14	0.13
Carpet	13,400[m]	26.8	17.8%	16.3%	0.077	0.37	0.34
Personal Computers	1,533[n]	3.1	17.8%	16.3%	0.077	0.04	0.04
Tires	11,769[o]	25.9	17.8%	16.3%	0.077	NA	1.98

Note that totals may not sum due to independent rounding, and more digits may be displayed than are significant.

[a] EPA developed these estimates based on data on the specific heat of aluminum, steel, and glass and calculated the energy required to raise the temperature of aluminum, steel, and glass from ambient temperature to the temperature found in a combustor (about 750° Celsius). EPA obtained the specific heat data from Incropera, Frank P. and David P. DeWitt, Introduction to Heat Transfer, Second Edition (New York: John Wiley & Sons), 1990, pp. A3-A4.

[b] MSW Fact Book.

[c] Gaines and Stodolsky.

[d] For PET plastic, EPA converted the value of 9,900 Btu/lb. dry weight, to 9,702 Btu/lb. wet weight, to account for a moisture content of 2 percent.

[e] Franklin Associates, Ltd.'s value for magazines used as a proxy for the value for magazines/third-class mail.

[f] The MSW Fact Book's value for mixed paper used as a proxy for the value for office paper.

[g] Newspapers used as a proxy for phonebooks.

[h] Office paper used as a proxy for textbooks.

[i] EPA used the higher end of the Btu factor for Basswood from the USDA-FS. Basswood is a relatively soft wood, so its high-end Btu content should be similar to an average factor for all wood types. Fons, W. L., et al. 1962. Project Fire Model. Summary Progress Report-II. Period May 1, 1960, to April 30, 1962. Macon, GA: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Southern Forest Fire Laboratory. 58 pp. [16824]

[j] Proctor and Redfern, Ltd. and ORTECH International.

[k] Telephone conversation among IWSA, American Ref-Fuel, and ICF Consulting, October 28, 1997.

[l] Mixed MSW represents the entire waste stream as disposed of.

[m] Franklin Associates, Ltd., 2002, "Energy and Greenhouse Gas Factors for Nylon Broadloom Residential Carpet."

[n] Franklin Associates, Ltd., 2002, "Energy and Greenhouse Gas Factors for Personal Computers."

[o] Tires used as tire-derived fuel substitute for coal in cement kilns, electric utilities; and a substitute for natural gas in pulp and paper facilities.

[p] The amount of energy absorbed by 1 ton of steel, aluminum cans, or glass in an MSW combustor would, if not absorbed, result in less than 0.01 MTCE of avoided utility CO_2.

Next, losses in transmission and distribution of electricity were considered. Using a transmission and distribution loss rate of 5 percent,[27] EPA estimated that 523 kWh are delivered per ton of waste combusted at mass burn facilities, and 544 kWh are delivered per ton of waste input at RDF facilities

EPA then used the value for the delivered kWh per ton of waste combusted to derive the implicit combustion system efficiency (i.e., the percentage of energy in the waste that is ultimately delivered in the form of electricity). To determine this efficiency, the Btu of MSW needed to deliver 1 kWh of electricity was estimated. EPA divided the Btu per ton of waste by the delivered kWh per ton of waste to obtain the Btu of waste per delivered kWh. The result is 19,200 Btu per kWh for mass burn and 21,000 Btu per kWh for RDF. The physical constant for the energy in 1 kWh (3,412 Btu) then was divided by the Btu of MSW and RDF needed to deliver 1 kWh, to estimate the total system efficiency at 17.8 percent for mass burn and 16.3 percent for RDF (Exhibit 5-2, columns "d" and "e").[28]

Electric utility carbon emissions avoided: To estimate the avoided utility CO_2 from waste combustion, EPA used the results in columns "c" and "d," together with a "carbon coefficient" of 0.081 MTCE emitted per million Btu of utility-generated electricity (delivered), based on the national average fossil fuel mix used by utilities[29] as shown in Exhibit 5-3 and Exhibit 5-5. This approach uses the average fossil fuel mix as a proxy for the fuels displaced at the margin when utility-generated electricity is displaced by electricity from WTE plants. In other words, EPA assumes that nuclear, hydropower, and other nonfossil sources generate electricity at essentially fixed rates; marginal demand is met by fossil sources.[30] (In practice, the type of fuel displaced at the margin is not always fossil, with varying consequences on carbon reductions.) The resulting estimates for utility carbon emissions avoided for each material are shown in columns "g" and "h" of Exhibit 5-2.

5.1.6 Approach to Estimating CO_2 Emissions Avoided Due to Steel Recycling

Next, the study estimated the avoided CO_2 emissions from increased steel recycling made possible by steel recovery from WTE plants for (1) mixed MSW and (2) steel cans. Note that EPA did not credit increased recycling of nonferrous materials, because of lack of data on the proportions of those materials being recovered. The result tends to overestimate net GHG emissions from combustion.

For mixed MSW, EPA estimated the amount of steel recovered per ton of mixed MSW combusted, based on (1) the amount of MSW combusted in the United States, and (2) the amount of steel recovered, postcombustion. Ferrous metals are recovered at approximately 89 WTE facilities in the United States and at five RDF processing facilities that do not generate power on-site. These facilities recovered a total of nearly 706,000 tons per year of ferrous metals in 2004.[31] By dividing 706,000 tons (total U.S. steel recovery at combustors) by total U.S. combustion of MSW, which is nearly 29 million tons, EPA estimated that 0.03 tons of steel are recovered per ton of mixed MSW combusted (as a national average).

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[27] Personal communication among representatives of Integrated Waste Services Association, American Ref-Fuel, and ICF Consulting, October 28, 1997.

[28] Note that the total system efficiency is the efficiency of translating the energy content of the fuel into the energy content of delivered electricity. The estimated system efficiencies of 17.8 and 16.3 percent reflect losses in (1) converting energy in the fuel into steam, (2) converting energy in steam into electricity, and (3) delivering electricity. The losses in delivering electricity are the transmission and distribution losses, estimated at 5 percent.

[29] Value estimated using data from the Energy Information Administration, *Annual Energy Review 2004* (Washington, DC: U.S. Government Printing Office, DOE/EIA-0384(2000)), 2005.

[30] Nonfossil sources are expected to meet baseload energy requirements because of the financial incentive for these energy sources to generate at capacity. In general, the marginal cost of producing more power from these sources is minimal compared to the capital costs associated with establishing the facility.

[31] Integrated Waste Services Association, *The 2004 IWSA Waste-To-Energy Directory of United States Facilities.*

For steel cans, EPA first estimated the national average proportion of steel cans entering WTE plants that would be recovered. As noted above, approximately 90 percent of MSW destined for combustion goes to facilities with a ferrous recovery system. At these plants, approximately 98 percent of the steel cans are recovered. EPA multiplied these percentages to estimate the weight of steel cans recovered per ton of MSW combusted—about 0.88 tons recovered per ton combusted.

Finally, to estimate the avoided CO_2 emissions due to increased recycling of steel, EPA multiplied (1) the weight of steel recovered by (2) the avoided CO_2 emissions per ton of steel recovered. The result was estimated avoided CO_2 emissions of approximately 0.43 MTCE per ton for steel cans and 0.01 MTCE per ton for mixed MSW, as shown in column "d" of Exhibit 5-5.

Exhibit 5-3
Estimating the Weighted Average Carbon Coefficient of the U.S. Average Mix of Fuels Used to Generate Electricity (MTCE/Million Btu)

Fuel	Primary Energy Consumption[a] (Quads)	Percentage of Generation: All Fuels (%)	Percentage of Generation: Fossil Fuels (%)	Carbon Coefficents[b] (Kg CE Emitted Per Million Btu Consumed)
Coal[c]	20.6	50.5%	73%	25.72
Natural Gas	6.2	15.2%	22%	14.33
Petroleum[d]	1.3	3.1%	5%	21.28
Nuclear	8.2	20.2%		0
Renewable	4.3	10.5%		0
Other	0	0.5%		0
Total	**40.8**	**100%**	**100%**	**NA**
Weighted Average - All Fuels				15.83
Weighted Average - Fossil Fuels				23.01

Note that totals may not sum due to independent rounding, and more digits may be displayed than are significant.

[a] Source: EIA's Annual Energy Review: 2004, "Electricity Flow," for 2004.

[b] Values include fugitive CH_4 emissions (weighted by the GWP of CH_4).

[c] Carbon coefficient based on 49% bituminous, 43% sub-bituminous; 8% lignite.

[d] The carbon coefficient for residual fuel is used as a proxy for petroleum.

Exhibit 5-4
Estimating the Emission Factor for Utility Generated Electricity

Fuel	Primary Energy Consumption (Quads)[a]	Electricity Net Generation (BkWh)[a]	Implied Heat Rate (Btu/kWh)	Fossil-Only Weighted Heat Rate (Btu/kWh)[b]	National Average Weighted Heat Rate (Btu/kWh)[b]
Coal	20.6	1,954	10,532	7,730	5,319
Natural Gas	6.2	619	9,990	2,202	1,515
Petroleum	1.3	113	11,378	519	357
Nuclear	8.2	789	10,436		2,108
Renewable	4.3	315	13,564		1,421
Other	0				
Total	40.8				

Electricity Generation Fuel Mix	Fossil-Only	National Average
Generated Electricity Average Heat Rate (Btu/kWh)[c]	10,451	10,721
Average Fuel Mix Carbon Coefficient (kg CE/MMBtu)[d]	23.01	15.83
Generated Electricity Emission Factor (kg CE/kWh)[e]	0.24	0.17
Generated Electricity Emission Factor (kg CE/MMBtu)[f]	70.49	49.75
Generated Electricity Emission Factor (MTCE/MMBtu)	0.070	0.05

[a] EIA. 2005. Annual Energy Review: 2004. (Table 8.4a and 8.2b)

[b] Weighted by percent of total primary energy consumption.

[c] Sum of the weighted heat rate values for each fuel type above.

[d] Carbon coefficient weighted average by primary energy consumption (See table 5-3)

[e] Average heat rate multiplied by the average fuel mix carbon coefficient. (National average value is equal to 1.37 pounds CO_2E/kWh)

[f] Converted from kWh to Btu using the heatless constant of 3,412 Btu/kWh.

Exhibit 5-5
Avoided GHG Emissions Due to Increased Steel Recovery from MSW at WTE Facilities

(a) Material Combusted	(b) Tons of Steel Recovered Per Ton Of Waste Combusted (Tons)	(c) Avoided CO_2 Emissions Per Ton Of Steel Recovered (MTCE/Ton)	(d) Avoided CO_2 Emissions Per Ton Of Waste Combusted (MTCE/Ton)[a]
Aluminum Cans	0.00	0.00	0.00
Steel Cans	0.88	0.49	0.43
Copper Wire	0.00	0.00	0.00
Glass	0.00	0.00	0.00
HDPE	0.00	0.00	0.00
LDPE	0.00	0.00	0.00
PET	0.00	0.00	0.00
Corrugated Cardboard	0.00	0.00	0.00
Magazines/Third-class Mail	0.00	0.00	0.00
Newspaper	0.00	0.00	0.00
Office Paper	0.00	0.00	0.00
Phonebooks	0.00	0.00	0.00
Textbooks	0.00	0.00	0.00
Dimensional Lumber	0.00	0.00	0.00
Medium-density Fiberboard	0.00	0.00	0.00
Food Discards	0.00	0.00	0.00
Yard Trimmings	0.00	0.00	0.00
Mixed Paper[b]			
Broad Definition	0.00	0.00	0.00
Residential Definition	0.00	0.00	0.00
Office Paper Definition	0.00	0.00	0.00
Mixed MSW	0.03	0.49	0.01
Carpet	0.00	0.00	0.00
Personal Computers	0.25	0.49	0.12
Tires[c]	0.06	0.49	0.03

Note that totals may not sum due to independent rounding, and more digits may be displayed than are significant.

[a] The value in column "d" is a national average and is weighted to reflect 98 percent recovery at the 90 percent of facilities that recover ferrous metals.

[b] The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.

[c] Assumes only 48 percent of facilities that use TDF recover ferrous metals.

5.2 RESULTS

The results of this analysis are shown in Exhibit 5-6. The results from the last column of Exhibit 5-1, the last two columns of Exhibit 5-2, and the last column of Exhibit 5-5 are shown in columns "b" through "e" in Exhibit 5-6. The net GHG emissions from combustion of each material at mass burn and RDF facilities are shown in columns "f" and "g," respectively. These net values represent the gross GHG emissions (column "b"), minus the avoided GHG emissions (columns "c," "d," and "e"). As stated earlier, these estimates of net GHG emissions are expressed for combustion in absolute terms. They are not values relative to some other waste management option. They are expressed in terms of short tons of waste input (i.e., tons of waste prior to processing).

EPA estimates that combustion of mixed MSW at mass burn and RDF facilities reduces net postconsumer GHG emissions to -0.03 and -0.02 MTCE per ton, respectively. Combustion of paper products has negative net postconsumer GHG emissions ranging from -0.13 to -0.20 MTCE per ton at mass burn facilities and from -0.12 to -0.18 MTCE per ton at RDF facilities. Net GHG emissions are negative because CO_2 emissions from burning paper are not counted (because they are biogenic) and fossil fuel burning by utilities to generate electricity is avoided. Likewise, combustion of medium-density fiberboard and dimensional lumber also results in negative net GHG emissions, with both equaling -0.21 MTCE per ton at mass burn facilities and -0.19 MTCE per ton at RDF facilities. Finally, net GHG emissions for food discards and yard trimmings (two other forms of biomass) are also negative, but of a smaller magnitude (-0.05 and -0.06 MTCE per ton of material, respectively, for mass burn and -0.04 and -0.05 MTCE per ton of material, respectively, for RDF).

Combustion of plastics results in substantial net GHG emissions, estimated from 0.25 to 0.30 MTCE per ton of material combusted for mass burn facilities, and from 0.30 to 0.32 MTCE per ton of material input to RDF facilities. This result is primarily because of the high content of nonbiomass carbon in plastics. Also, when combustion of plastic results in electricity generation, the utility carbon emissions avoided (due to displaced utility fossil fuel combustion) are much lower than the carbon emissions from the combustion of plastic. This result is largely due to the lower system efficiency of WTE plants, compared with electric utility plants. Recovery of ferrous metals at combustors results in negative net GHG emissions, estimated at -0.42 MTCE per ton of steel cans, due to the increased steel recycling made possible by ferrous metal recovery at WTE plants.

5.3 LIMITATIONS

The certainty of the analysis presented in this chapter is limited by the reliability of the various data elements used. The most significant limitations are as follows:

- Combustion system efficiency of WTE plants may be improving. If efficiency improves, more utility CO_2 will be displaced per ton of waste combusted (assuming no change in utility emissions per kWh), and the net GHG emissions from combustion of MSW will decrease.
- Data for the RDF analysis were provided by the Minnesota Office of Environmental Assistance and were obtained from a single RDF processing facility and a separate RDF combustion facility. Research indicates that each RDF processing and combustion facility is different. For example, some RDF combustion facilities may generate steam for sale off-site, which can affect overall system efficiency. In addition, the amount of energy required to process MSW into RDF and the amount of energy used to operate RDF combustion facilities can be difficult to quantify and can vary among facilities on a daily, seasonal, and annual basis. Thus, the values used for the RDF analysis should be interpreted as approximate values.

Exhibit 5-6
Net GHG Emissions from Combustion at WTE Facilities

(a) Material Combusted	(b) Gross GHG Emissions Per Ton Combusted (MTCE/Ton)	(c) Avoided Utility CO_2 Per Ton Combusted at Mass Burn Facilities (MTCE/Ton)	(d) Avoided Utility CO_2 Per Ton Combusted at RDF Facilities (MTCE/Ton)	(e) Avoided CO_2 Emissions Per Ton Combusted Due to Steel Recovery (MTCE/Ton)	(f) (f = b - c - e) Net GHG Emissions from Combustion at Mass Burn Facilities (MTCE/Ton)	(g) (g = b - d- e) Net GHG Emissions from Combustion at RDF Facilities (MTCE/Ton)
Aluminum Cans	0.01	-0.01	-0.01	0.00	0.02	0.02
Steel Cans	0.01	-0.01	-0.01	0.43	-0.42	-0.42
Copper Wire	0.01	-0.01	-0.01	0.00	0.01	0.01
Glass	0.01	-0.01	-0.01	0.00	0.01	0.01
HDPE	0.77	0.52	0.47	0.00	0.25	0.30
LDPE	0.77	0.52	0.47	0.00	0.25	0.30
PET	0.56	0.27	0.24	0.00	0.30	0.32
Corrugated Cardboard	0.02	0.19	0.18	0.00	-0.18	-0.16
Magazines/Third-class Mail	0.02	0.15	0.13	0.00	-0.13	-0.12
Newspaper	0.02	0.22	0.20	0.00	-0.20	-0.18
Office Paper	0.02	0.19	0.17	0.00	-0.17	-0.15
Phonebooks	0.02	0.22	0.20	0.00	-0.20	-0.18
Textbooks	0.02	0.19	0.17	0.00	-0.17	-0.15
Dimensional Lumber	0.02	0.23	0.21	0.00	-0.21	-0.19
Medium-density Fiberboard	0.02	0.23	0.21	0.00	-0.21	-0.19
Food Discards	0.02	0.07	0.06	0.00	-0.05	-0.04
Yard Trimmings	0.02	0.08	0.07	0.00	-0.06	-0.05
Mixed Paper[a]						
Broad Definition	0.02	0.20	0.18	NA	-0.18	-0.16
Residential Definition	0.02	0.19	0.18	NA	-0.18	-0.16
Office Paper Definition	0.02	0.18	0.16	NA	-0.16	-0.15
Mixed MSW	0.12	0.14	0.13	0.01	-0.03	-0.02
Carpet	0.48	0.37	0.34	0.00	0.11	0.14
Personal Computers	0.11	0.04	0.04	0.12	-0.05	-0.05
Tires[b]	2.06	NA	1.98	0.03	NA	0.05

Note that totals may not sum due to independent rounding, and more digits may be displayed than are significant.
[a] The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.
[b] Tires used as TDF substitute for coal in cement kilns, electric utilities; and a substitute for natural gas in pulp and paper facilities.

The reported ranges for N_2O emissions were broad. In some cases the high end of the range was 10 times the low end of the range. Research has indicated that N_2O emissions vary with the type of waste burned. Thus, the average value used for mixed MSW and for all MSW components should be interpreted as an approximate value.

- For mixed MSW, the study assumed that all carbon in textiles is from synthetic fibers derived from petrochemicals (whereas, in fact, some textiles are made from cotton, wool, and other natural fibers). Because EPA assumed that all carbon in textiles is nonbiogenic, all of the CO_2 emissions from combustion of textiles as GHG emissions were counted. This assumption will slightly overstate the net GHG emissions from combustion of mixed MSW, but the magnitude of the error is small because textiles represent only a small fraction of the MSW stream. Similarly, the MSW category of "rubber and leather" contains some biogenic carbon from leather and natural rubber. By not considering this small amount of biogenic carbon, the analysis slightly overstates the GHG emissions from MSW combustion.

- Because the makeup of a given community's mixed MSW may vary from the national average, the energy content also may vary from the national average energy content used in this analysis. For example, MSW from communities with a higher- or lower-than-average recycling rate may have a different energy content, and MSW with more than the average proportion of dry leaves and branches will have a higher energy content.

- In this analysis, EPA used the national average recovery rate for steel. Where waste is sent to a WTE plant with steel recovery, the net GHG emissions for steel cans will be slightly lower (i.e., more negative). Where waste is sent to a WTE plant without steel recovery, the net GHG emissions for steel cans will be the same as for aluminum cans (i.e., close to zero). EPA did not credit increased recycling of nonferrous materials, because of a lack of information on the proportions of those materials. This assumption tends to result in overstated net GHG emissions from combustion.

- This analysis used the national average fossil fuel mix for electricity as the proxy for fuel displaced at the margin when WTE plants displace utility electricity. If some other fuel or mix of fuels is displaced at the margin (e.g., coal), the avoided utility CO_2 would be different (e.g., for coal, the avoided utility CO_2 would be about 0.01 MTCE per ton higher for mixed MSW, and the net GHG emissions would be -0.04 MTCE instead of -0.03 MTCE per ton).

6. LANDFILLING

This chapter presents estimates of GHG emissions and carbon storage from landfilling the materials considered in this analysis. For this study, EPA estimated the CH_4 emissions, transportation-related CO_2 emissions, and carbon storage that will result from landfilling each type of organic waste and mixed MSW. The analysis is based on three key GHG accounting principles:[1]

- When food discards, yard trimmings, paper, and wood are landfilled, anaerobic bacteria degrade the materials, producing CH_4 and CO_2. CH_4 is counted as an anthropogenic GHG, because even though it is derived from sustainably harvested biogenic sources, degradation would not result in CH_4 emissions if not for deposition in landfills. The CO_2 is not counted as a GHG in this context because if it were not emitted from landfills, it would be produced through natural decomposition. Because metals and glass do not contain carbon, they do not generate CH_4 when landfilled. Plastics, carpet, PCs, clay bricks, concrete, fly ash, and tires do not biodegrade measurably in anaerobic conditions, and therefore do not generate any CH_4.
- Transportation of waste materials to a landfill results in anthropogenic CO_2 emissions, due to the combustion of fossil fuels in the vehicles used to haul the wastes.
- Because food discards, yard trimmings, and paper are not completely decomposed by anaerobic bacteria, some of the carbon in these materials is stored in the landfill. Because this carbon storage would not normally occur under natural conditions (virtually all of the organic material would degrade to CO_2, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic sink. However, carbon in plastic that remains in the landfill is not counted as stored carbon, because it is of fossil origin.

EPA developed separate estimates of emissions from (1) landfills without gas recovery systems, (2) those that flare CH_4, (3) those that combust CH_4 for energy recovery, and (4) the national average mix of these three categories. The national average emission estimate accounts for the extent to which CH_4 will be flared at some landfills and combusted onsite[2] for energy recovery at others.[3]

From the standpoint of postconsumer GHG emissions, landfilling some materials—including newspaper and phonebooks—results in net storage (i.e., carbon storage exceeds CH_4 plus transportation energy emissions) at all landfills, regardless of whether gas recovery is present. At the other extreme, office paper, textbooks, and food discards result in net emissions regardless of landfill gas collection and recovery practices. The remaining materials have net postconsumer emissions that are either very low (all materials have transportation-related emissions of 0.01 MTCE per ton, regardless of whether gas collection is present) or borderline, depending on whether the landfill has gas recovery (e.g., mixed MSW has net emissions at landfills without gas recovery, but net carbon storage at landfills with gas recovery).

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[1] These principles are described in broad terms in Section 1.4 of this report.

[2] Although gas from some landfills is piped to an offsite power plant and combusted there, for the purposes of this report, the assumption was that all gas for energy recovery was combusted onsite.

[3] Currently, most landfill CH_4 recovery in the United States—both for flaring and electricity—is occurring in response to a 1996 EPA rule that requires a well-designed and well-operated landfill gas collection system at landfills that (1) have a design capacity of at least 2.5 million metric tons and 2.5 million cubic meters; (2) are calculated to emit more than 50 metric tons of non-CH_4 organic compounds per year; and (3) received waste on or after November 11, 1987 (*Federal Register*, Vol. 61, No. 49, p. 9905, March 12, 1996). For the year 2003, an estimated 59 percent of landfill CH_4 was generated at landfills with landfill gas recovery systems subject to these requirements or installed on a voluntary basis (U.S. Environmental Protection Agency, 2005. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*).

6.1 CH_4 GENERATION AND CARBON STORAGE FOR ORGANIC MATERIALS

This section starts with a review of the principal processes that influence the fate of organic carbon in the landfill environment and then describes the experimental basis for and derivation of the estimates of CH_4 emissions and carbon storage used in this report.

6.1.1 Carbon Stocks and Flows in Landfills

Exhibit 6-1 shows the carbon flows within a landfill system. Carbon entering the landfill can have one of several fates: exit as CH_4, exit as CO_2, exit as volatile organic compounds (VOCs), exit dissolved in leachate, or remain stored in the landfill.[4]

After entering landfills, a portion of the organic materials decomposes and eventually is transformed into landfill gas and/or leachate. Aerobic bacteria initially decompose the waste until the available oxygen is consumed. This stage usually lasts less than a week and is followed by the anaerobic acid state, in which carboxylic acids accumulate, the pH decreases, and some cellulose and hemicellulose decomposition occurs. Finally, during the methanogenic state, bacteria further decompose the organic material into CH_4 and CO_2.

The rate of decomposition in landfills is affected by a number of factors, including: (1) waste composition; (2) factors influencing microbial growth (moisture, available nutrients, pH, temperature); and (3) whether the operation of the landfill retards or enhances waste decomposition. Most studies have shown the amount of moisture in the waste, which can vary widely within a single landfill, to be a critical factor in the rate of decomposition.[5] As a result, there is increasing interest in the operation of landfills as bioreactors, in which leachate and possibly other liquids are recirculated to enhance decomposition and gas production.[6] Bioreactor technologies, which optimize landfill moisture content in order to accelerate waste decomposition, have emerged as a leading technology for facilitating rapid decomposition of organic wastes and cost-effective CH_4 collection.

Of the various components of the landfill carbon system, by far the most research to date has been conducted on the transformation of landfill carbon into CH_4.[7,8] This interest has been spurred by a number of factors, including EPA's 1996 rule requiring large landfills to control landfill gas emissions (40 Code of Federal Regulations Part 60, Subparts Cc and WWW), the importance of CH_4 emissions in GHG inventories, and the market for CH_4 as an energy source. CH_4 production occurs in the methanogenic stage of decomposition, as methanogenic bacteria break down the fermentation products from earlier decomposition processes. Since CH_4 emissions result from waste decomposition, the quantity and duration of the emissions is dependent on the same factors that influence waste degradability (e.g., waste composition, moisture).

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[4] The exhibit and much of the ensuing discussion are taken directly from Freed, J.R., K. Skog, C. Mintz, and N. Glick. 2004. "Carbon Storage due to Disposal of Biogenic Materials in U.S. Landfills." *Proceedings of the Third Annual Conference on Carbon Sequestration*, U.S. Department of Energy. Available at www.carbonsq.com.

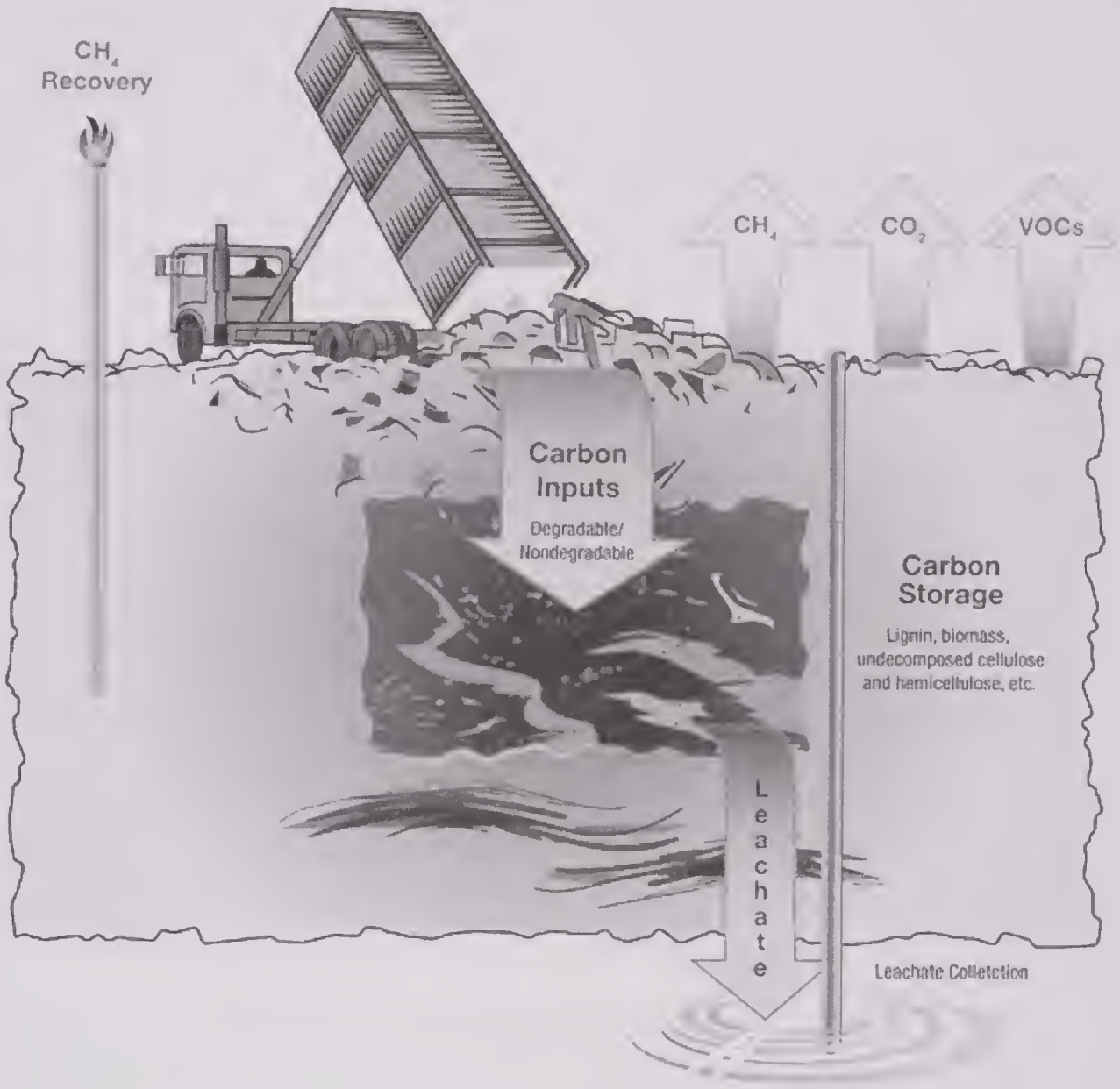
[5] Barlaz, M. A., R.K. Ham, and D.M. Schaefer. 1990. "Methane Production From Municipal Refuse: A Review of Enhancement Techniques and Microbial Dynamics," *Critical Reviews in Environmental Control, 19(6):557.*

[6] Pacey, J., D. Augenstein, R. Morck, D. Reinhart, R. Yazdani. 1999. The Bioreactive Landfill. *MSW Management*, September/October 1999.

[7] Bingemer, H G. and P J Crutzen, 1987. "The Production of Methane from Solid Wastes." *Journal of Geophysical Research* 90(D2): 2181-2187.

[8] Barlaz, M., W. Eleazer, W. Odle, X. Qian, Y. Wang. 1997. "Biodegradative Analysis of Municipal Solid Waste in Laboratory-Scale Landfills," U.S. Environmental Protection Agency 600/R-97-071.

Exhibit 6-1 Landfill Carbon Mass Balance



Carbon dioxide is produced in the initial aerobic stage and anaerobic acid stage of decomposition. However, relatively little research has been conducted to quantify CO_2 emissions during these stages. Emissions during the aerobic stage are generally assumed to be a small proportion of total organic carbon inputs, and a screening level analysis indicates that less than 1 percent of carbon is likely to be emitted through this pathway.[9] Once the methanogenic stage of decomposition begins, landfill gas *as generated* is composed of approximately 50 percent CH_4 and 50 percent CO_2.[10] But landfill gas *as collected* generally has a higher CH_4 concentration than CO_2 concentration (sometimes as much as a 60 percent:40 percent ratio), because some of the CO_2 is dissolved in the leachate as part of the carbonate system ($CO_2 \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- \leftrightarrow CO_3^{2-}$).

To date, very little research has been conducted on the role of VOC emissions in the landfill carbon mass balance. Given the thousands of compounds entering the landfill environment, tracking the biochemistry by which these compounds ultimately are converted to VOC is a complex undertaking. Existing research indicates that ethane, limonene, *n*-decane, *p*-dichlorobenzene, and toluene may be

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[9] Freed et al. 2004. Op cit.
[10] Bingemer, H. G. and P. J. Crutzen, 1987. Op. cit.

among the most abundant landfill VOCs.[11] Hartog (2003) reported non-CH_4 volatile organic compound concentrations in landfill gas at a bioreactor site in Iowa, averaging 1,700 parts per million (ppm) carbon by volume in 2001 and 925 ppm carbon by volume in 2002.[12] If the VOC concentrations in landfill gas are generally of the order of magnitude of 1,000 ppm, VOCs would have a small role in the overall carbon balance, as concentrations of CH_4 and CO_2 will both be hundreds of times larger.

Leachate is produced as water percolates through landfills. Factors affecting leachate formation include the quantity of water entering the landfill, waste composition, and the degree of decomposition. Because it may contain materials capable of contaminating groundwater, leachate (and the carbon it contains) is typically collected and treated before being released to the environment, where it eventually degrades into CO_2. However, leachate is increasingly being recycled into the landfill as a means of inexpensive disposal and to promote decomposition while the containment system is operating at peak efficiency.[13] Research shows that this recirculation can increase the mass of organics collected by the system and consequently enhance aqueous degradation.[14] Although a significant body of literature exists on landfill leachate formation, little research is available on the carbon implications of this process. Based on a screening analysis, Freed et al. (2004) found that loss as leachate may occur for less than one percent of total carbon inputs to landfills.

In mass balance terms, carbon storage can be characterized as the carbon that remains after accounting for the carbon exiting the system as landfill gas or dissolved in leachate. On a dry weight basis, municipal refuse contains 30–50 percent cellulose, 7–12 percent hemicellulose, and 15–28 percent lignin.[15] Although the degradation of cellulose and hemicellulose in landfills is well documented, lignin does not degrade to a significant extent under anaerobic conditions.[16] In fact, although cellulose and hemicellulose biodegradation does occur, the extent of decomposition varies with landfill conditions, and these materials do not appear to completely degrade based on a number of excavation studies.[17] In addition, the presence of lignin actually prevents some cellulose and hemicellulose biodegradation. Thus, landfills in effect store some of the cellulose and hemicellulose and all of the lignin that is buried initially. The amount of storage will vary with environmental conditions in the landfill; pH and moisture content have been identified as the two most important variables controlling decomposition.[18]

6.1.2 Measured and Estimated CH_4 Generation and Carbon Storage

The focus of this report is on comparing waste management options for specific materials within the solid waste stream. Although a large body of research exists on CH_4 generation from mixed solid wastes, only a few investigators—most notably Dr. Morton Barlaz and coworkers at North Carolina State University—have measured the behavior of specific waste wood, paper, food waste, and yard trimming components.

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[11] Eklund B., E. Anderson, B. Walker, and D. Burrows.1998. "Characterization of landfill gas composition at the Fresh Kills municipal solid-waste landfill." *Environ Sci Technol* 32:2233-2237.
[12] Hartog, C.L. 2003. The Bluestem Bioreactor. Briefing presented at the Bioreactor Workshop, sponsored by USEPA, Feb 27-28, 2003, Arlington, VA.
[13] Chan G., L. Chu, and M. Wong. 2002. "Effects of leachate recirculation on biogas production from landfill co-disposal of municipal solid waste, sewage sludge and marine sediment." *Environmental Pollution* 118(3). 393–399.
[14] Warith, M. A., W. Zekry, and N. Gawri. 1999. "Effect of leachate recirculation on municipal solid waste biodegradation," *Water Quality Research Journal of Canada* Volume 34, No. 2, pp. 267–280.
[15] Hilger, H., and M. Barlaz. 2001. "Anaerobic decomposition of refuse in landfills and methane oxidation in landfill cover soils," *Manual of Environmental Microbiology*, 2nd Ed., Am. Soc. Microbiol., Washington, D. C., pp. 696–718.
[16] Colberg, P.J. 1988. "Anaerobic microbial degradation of cellulose lignin, oligolignols, and monoaromatic lignin derivatives." p. 333–372. *In* A.J.B. Zehnder (ed.) Biology of anaerobic microorganisms. New York: Wiley.
[17] Ham, R.K., and Bookter T.J. 1982. "Decomposition of solid waste in test lysimeters." *J.Env. Eng.* 108: 1147.
[18] Barlaz, M. A., R. Ham, and D. Schaefer. 1990. Op cit.

Barlaz[19] developed a series of laboratory experiments designed to measure biodegradation of these materials in a simulated landfill environment, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). Specific waste components (e.g., grass, branches, leaves, paper) were dried, analyzed for cellulose, hemicellulose, and lignin content, weighed, placed in two-liter plastic containers (i.e., reactors), and allowed to decompose anaerobically under moist conditions (Eleazer, et al. 1997).[20] The reactors were seeded with a small amount of well-decomposed refuse containing an active population of microorganisms. Phosphate and nitrogen concentrations were maintained at sufficient levels to assure that they were not limiting factors for biodegradation. The reactors were allowed to run until either no more CH_4 was produced or an extrapolation of gas production data indicate that the reactors had produced 95 percent of the CH_4 that would ultimately be emitted if allowed to run forever. At the end of the experiment, the contents of the reactors were dried, weighed, and analyzed for cellulose, hemicellulose, lignin, and (in the case of grass only) protein content. The carbon in these residual components is assumed to represent carbon that would remain undegraded over the long term in landfills; i.e., it would be stored.

Thus, these experiments provide three key outputs on a material-by-material basis: initial carbon content (namely, the sum of carbon in the cellulose, hemicellulose, lignin, and protein components), cumulative CH_4 emissions (over the course of the experiment), and carbon stored (as of the end of the experiment).[21]

As described in the preceding section, the principal elements in the landfill carbon balance are:

- Initial carbon content;
- Carbon output as CH_4 (CH_4-C);
- Carbon output as CO_2 (CO_2-C); and
- Residual carbon (i.e., landfill carbon storage, LF C).

Of these elements, the only one missing in the Barlaz experiments is CO_2 emissions. In a simple system where the only carbon fates are CH_4, CO_2, and carbon storage, the carbon balance can be described as

$$CH_4 - C + CO_2 - C + LF\ C = Initial\ C$$

If the only decomposition is anaerobic, then CH_4-C = CO_2-C.[22] Thus, the carbon balance can be expressed as

$$2 \times CH_4 - C + LF\ C = Initial\ C$$

Exhibit 6-2 shows the measured experimental values, in terms of the percentage of initial carbon, for each of the materials analyzed (see columns "b" and "d"). The exhibit also displays the implied biogas yield (= 2 × CH_4 - C, column "c"), and the sum of outputs (= 2 × CH_4 - C + LF C) as a percentage of initial carbon (see column "e"). As column "e" shows, the balance between carbon outputs and carbon inputs generally was not perfect; the imbalance ranges from 0 percent of initial carbon for newsprint to 34 percent of initial carbon for office paper, and is attributable to measurement uncertainty in the analytic techniques.

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[19] Barlaz, M.A., 1998. "Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills." *Global Biogeochemical Cycles* 12 (2), 373-380.

[20] Eleazer, W.E., W.S. Odle, III, Y.S. Wang, and M.A. Barlaz. 1997. "Biodegradability of municipal solid waste components in laboratory-scale landfills." *Env. Sci. Tech.* 31(3):911–917.

[21] It should be noted that VOCs are also emitted, but are estimated to account for less than one percent of carbon flux from landfills. (Freed, J.R., K. Skog, N. Glick, C. Mintz. 2004. *Carbon Storage due to Disposal of Biogenic Materials in U.S. Landfills*. Proceedings of the Third Annual Conference on Carbon Sequestration. U.S. Dept of Energy, National Energy Technology Lab.)

[22] The molar ratio of CH_4 to CO_2 is 1:1 for carbohydrates (e.g., cellulose, hemicellulose). For proteins, the molar ratio is 1.65 CH_4 per 1.55 CO_2; for protein it is $C_{3.2}H_5ON_{0.86}$ (Barlaz et al. 1989). Given the predominance of carbohydrates, for all practical purposes, the overall ratio is 1:1.

For the emission factors used in this report, adjustments were made to the measured values so that exactly 100 percent of the initial carbon would be accounted for. After consultation with Dr. Barlaz, the following approach was adopted:

- For materials where carbon outputs were *less than* initial carbon, the "missing" carbon was assumed to be emitted as equal molar quantities of CH_4 and CO_2. In these cases (corrugated cardboard, office paper, food discards, leaves, branches, and mixed MSW) the CH_4-C was increased with respect to the measured values as follows:

  $$(\text{Initial C} - \text{LF C}) / 2 = CH_4 - C$$

  This calculation assumes that CO_2-C = CH_4-C. In essence, the adjustment approach was to increase biogas production. The resulting values are italicized in column "g" of Exhibit 6-2.

- For materials where carbon outputs were *greater than* initial carbon (coated paper and grass), the measurements of initial carbon content and CH_4 mass were assumed to be accurate. Here, the adjustment approach was to decrease carbon storage. Thus, landfill carbon storage was calculated as the residual of initial carbon content minus (2 × CH_4-C). The resulting values are italicized in column "h" of Exhibit 6-2.

Exhibit 6-2
Experimental and Adjusted Values for CH_4 Yield and Carbon Storage.[a]

	Initial Carbon Content, % Of dry Matter	Measured Yield as a % Of Initial Carbon	Implied Yield Of Biogas (CH_4+CO_2) as Proportion Of Initial Carbon	Measured Proportion of Initial Carbon Stored	Output as % of Initial Carbon	Adjustment Approach	Adjusted Yield of CH_4 as Proportion Of Initial Carbon	Adjusted Proportion Of Initial Carbon Stored
	a	b	c (=2×b)	d	e (=c+d)	f	g	h
Paper and Paperboard								
Corrugated	46%	16%	32%	55%	88%	inc biogas	*22%*	55%
Newsprint	49%	8%	15%	85%	100%	NA	8%	85%
Office Paper	40%	27%	54%	12%	66%	inc biogas	*44%*	12%
Coated Paper	34%	12%	25%	99%	124%	reduce LF C	12%	*75%*
Food Discards	50%	30%	59%	16%	75%	inc biogas	*42%*	16%
Yard Trimmings								
Grass	44%	16%	32%	71%	103%	reduce LF C	16%	*68%*
Leaves	41%	7%	14%	72%	86%	inc biogas	*14%*	72%
Branches	49%	6%	13%	77%	90%	inc biogas	*12%*	77%
MSW	42%	11%	22%	52%	74%	inc biogas	*24%*	52%

[a] CH_4 generation estimates are from Eleazer, et al. (1997), op cit. Carbon storage and initial carbon content values are from Barlaz (1998), op cit. All values for leaves (initial carbon content, CH_4 generation, and carbon storage) are from updated experiments reported in a letter report from M.A. Barlaz to J.R. Freed (of ICF Consulting) dated June 29, 2005.

Exhibit 6-3
CH_4 Yield for Solid Waste Components

Material	Initial Carbon Content (%)	Final (Adjusted) C Emitted as CH_4 (%)	Final (Adjusted) CH_4 Yield (MTCE/dry ton)	Final (Adjusted) CH_4 Yield (MTCE/wet ton)
Corrugated Cardboard	47	22	0.80	0.688
Magazines/Third-class Mail	34	12	0.32	0.278
Newspaper	49	08	0.28	0.244
Office Paper	40	44	1.35	1.198
Food Discards	51	42	1.63	0.445
Yard Trimmings				0.264
Grass	45	16	0.55	0.150
Leaves	49	14	0.44	0.281
Branches	49	12	0.44	0.355
Mixed MSW	42	24	0.76	0.580

Exhibit 6-4
Carbon Storage for Solid Waste Components

(a) Material	(b) Ratio Of Carbon Storage to Dry Weight (gm C/dry gm)	(c) Ratio Of Dry Weight to Wet Weight (dry gm/wet gm)	(d) (d = b × c) Ratio Of Carbon Storage to Wet Weight (gm C/wet gm)	(e) Amount Of Carbon Stored (MTCE per Wet Ton)
Corrugated Cardboard	0.26	0.95	0.25	0.22
Magazines/Third-class Mail	0.26	0.95	0.25	0.22
Newspaper	0.42	0.95	0.40	0.36
Office Paper	0.05	0.95	0.05	0.04
Food Discards	0.08	0.30	0.02	0.02
Yard Trimmings				0.19
Grass	0.30	0.30	0.09	0.08
Leaves	0.30	0.70	0.21	0.19
Branches	0.38	0.90	0.34	0.31
Mixed MSW	0.22	0.84	0.18	0.17

Explanatory Notes:
(1) Because MSW is typically measured in terms of its wet weight, it was required to convert the ratios for carbon stored as a fraction of dry weight to carbon stored as a fraction of wet weight. To do this conversion, EPA used the estimated ratio of dry weight to wet weight for each material. These ratios are shown in column "c" of the exhibit. For most of the materials, EPA used data from an engineering handbook.[23] For grass, leaves, and branches, EPA used data provided by Dr. Barlaz.
(2) For consistency with the overall analysis, EPA converted the carbon storage values for each material to units of MTCE stored per short ton of waste material landfilled. The resulting values are shown in column "e" of the exhibit.

The CH_4 yields in column "g" of Exhibit 6-2 can be converted to yields expressed in MTCE/short ton (to be consistent with units in the rest of the report), as shown in Exhibit 6-3. Similarly, the carbon storage proportions listed in percentages in Exhibit 6-2 are converted to MTCE/wet ton in Exhibit 6-4.

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[23] Tchobanoglous, George, Hilary Theisen, and Rolf Eliassen. 1977. *Solid Wastes: Engineering Principles and Management Issues* (New York: McGraw-Hill Book Co.), pp. 58 and 60.

Dr. Barlaz's experiment did not specifically test all of the paper grades described in this report. He did evaluate four specific grades: newspaper, corrugated boxes, office paper, and coated paper. EPA identified proxies for five additional material types for which there were no experimental data. Magazines and third-class mail placed in a landfill were assumed to have characteristics similar to those observed for coated paper. Similarly, phonebooks and textbooks were assumed to behave in the same way as newspaper and office paper, respectively. Experimental results for branches were used as a proxy for dimensional lumber and medium-density fiberboard.

As discussed in Section 3.2, EPA included the following three definitions of mixed paper among the materials analyzed in this report:

- Broadly defined mixed paper, which includes almost all printing-writing paper, folding boxes, and most paper packaging;
- Residential mixed paper, which includes the typical mix of papers from residential curbside pick-up (e.g., high-grade office paper, magazines, catalogs, commercial printing, folding cartons, and a small amount of old corrugated containers); and
- Mixed paper from offices, which includes copy and printer paper, stationary and envelopes, and commercial printing.

To develop estimates of CH_4 emissions and carbon storage for these three categories of mixed paper, EPA used the detailed characterization of mixed paper (shown in Exhibit 3-2) developed by FAL, and assigned analogues among the four paper grades tested by Dr. Barlaz. Exhibit 6-5 characterizes the composition of the two products made from mixed paper: boxboard (made using either a broad or a residential mix of recycled paper) and paper towels (made from recycled office paper). Emissions were calculated using these characterizations of the mixed paper grades and the values obtained from Dr. Barlaz's experiment for newspaper, corrugated boxes, office paper, and coated paper.[24]

6.2 FATES OF LANDFILL CH_4

In this analysis, EPA accounted for (1) the oxidation in the landfill of some portion of landfill CH_4 to CO_2, and (2) the capture of CH_4, either for flaring or for combustion with energy recovery (in either case, the captured CH_4 is converted to CO_2).[25] Exhibit 6-6 presents this analysis.

The exhibit begins with the CH_4 generation per wet ton of each material, which is shown in column "b" (the values were simply copied from the last column of Exhibit 6-3). Columns "c" through "k" calculate net GHG emissions from CH_4 generation for each of three categories of landfills: (1) landfills without LFG recovery; (2) landfills with LFG recovery that flare LFG; and (3) landfills with LFG recovery that generate electricity from the LFG. Columns "l" through "n" show CH_4 generation-weighted percentage for each category in 2004.[26] The final column shows the weighted average GHG emissions from CH_4 generation across all types of landfills.

To estimate MSW CH_4 emissions from each category of landfill, EPA first estimated the percentage of landfill CH_4 that is oxidized near the surface of the landfill. Based on estimates in the literature, EPA assumed that 10 percent of the landfill CH_4 generated is either chemically oxidized or

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[24] Note that Exhibits 6-2 through 6-4 do not show mixed paper since this was not used as a category by Dr. Barlaz; however, mixed paper is shown in Exhibit 6-8 through Exhibit 6-10.

[25] The CO_2 that is emitted is not counted as a GHG because it is biogenic in origin (as described in "CO_2 Emissions from Biogenic Sources" in Section 1.4.2).

[26] U.S. Environmental Protection Agency, 2006. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004.*

converted by bacteria to CO_2,[27] and the remaining 90 percent remains as CH_4, and is either emitted or captured and burned.

Exhibit 6-5
Composition of Mixed Paper Categories from Barlaz Experiments (Percent)

Paper Grade	Broad Definition for Mixed Paper	Mixed Paper from Residential Sources	Mixed Paper from Offices
Corrugated Cardboard[a]	48	53	5
Magazines/Third-class Mail[b]	8	10	36
Newspaper[c]	24	23	21
Office Paper[d]	20	14	38
Total	100	100	100

Explanatory Notes:
[a] Includes virgin and recycled corrugated boxes.
[b] Includes coated free sheet paper and coated groundwood paper.
[c] Includes newspaper, uncoated groundwood paper, recycled folding boxes, and set-up boxes.
[d] Includes uncoated free sheet paper, cotton fiber paper, bleached bristols, unbleached kraft folding boxes, bleached kraft folding boxes, bleached bags and sacks, unbleached bags and sacks, and unbleached wrapping paper.

To estimate MSW CH_4 emissions from landfills with LFG recovery, EPA assumed that these landfills have an average LFG recovery efficiency of 75 percent.[28] EPA then calculated avoided utility GHG emissions from landfills where the CH_4 is used for electricity generation. Because energy recovery systems experience down time, during which CH_4 is flared rather than used to generate electricity, a 15 percent system efficiency loss was incorporated into the estimates for avoided utility emissions.[29]

EPA also estimated the percentage of CH_4 generated at each category of landfill in 2003. Research indicates that 59 percent of all landfill CH_4 was generated at landfills with recovery systems, and the remaining 41 percent was generated at landfills without LFG recovery.[30] Of the 59 percent of all CH_4 generated at landfills with LFG recovery, 53 percent (or 31 percent of all CH_4) was generated at landfills that use LFG to generate electricity, and 47 percent (or 28 percent of all CH_4) at landfills that flare LFG.[31, 32]

The results are shown in the final column of Exhibit 6-6. The materials with the highest rates of net GHG emissions from CH_4 generation, as shown in column "o"—corrugated boxes, office paper, and

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[27] An oxidation rate of 10 percent is cited by Liptay, K., J. Chanton, P. Czepiel, and B. Mosher, "Use of stable isotopes to determine methane oxidation in landfill cover soils," *Journal of Geophysical Research*, April 1998, 103(D7), pp. 8243-8250; and Czepiel, P.M., B. Mosher, P.M. Crill, and R.C. Harriss. 1996. "Quantifying the effects of oxidation on landfill methane emissions," *Journal of Geophysical Research*, 101, pp. 16721-16729. The rate of 10 percent is also recommended by the IPCC.
[28] EPA. 2005. The Landfill Methane Outreach Program (LMOP) has used this figure in its most recent publications [see, for example, *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions* (Washington, D.C.: U.S. Environmental Protection Agency) September 1999].
[29] EPA. 1999. *Landfill Gas-to-Energy Project Opportunities: Background Information on Landfill Profiles*, Office of Air and Radiation, EPA 430-K-99-002, pp. 3-13.
[30] Based on data on year 2004 MSW landfill CH_4 generation and collection data from *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004*) with an estimated landfill CH_4 recovery efficiency of 75 percent (from *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions*).
[31] *U.S. Greenhouse Gas Emissions and Sinks: 1990-2003.*
[32] The assumption that 59 percent of landfills recovering CH_4 will use it for energy is subject to change over time based upon changes in the cost of recovery and the potential payback. Additionally, new technologies may be developed that use recovered CH_4 for purposes other than generating electricity and direct gas use.

textbooks—also have the highest gross CH_4 generation, as shown in column "b." The recovery of CH_4 at landfills reduces the CH_4 emissions for each material in proportionate amounts but does not change the ranking of materials by CH_4 emissions. Grass, leaves, branches, and the two wood products have the lowest rates of net GHG emissions from CH_4 generation.

6.3 UTILITY CO_2 EMISSIONS AVOIDED

Exhibit 6-7 presents a list of conversion factors and physical constants used to convert CH_4 combusted for electricity production to avoided CO_2 emissions. Using data on Btu per cubic feet of CH_4, kWh of electricity generated and delivered per Btu, and kilograms of utility carbon avoided per Btu delivered, EPA estimated that 0.15 MTCE is avoided per MTCE of CH_4 combusted. This figure then was incorporated into Exhibit 6-8 to estimate net GHG emissions from landfills with electricity generation. As mentioned earlier in this chapter, the analysis assumes that 31 percent of CH_4 generated in the United States comes from landfills that combust landfill CH_4 for electricity generation. EPA also assumes a 15 percent system efficiency loss, reflecting the fact that landfill gas-to-energy facilities incur some system "down-time," as shown in column 1. Landfill CH_4 is assumed to be flared during down-time periods.

6.4 NET GHG EMISSIONS FROM LANDFILLING

To determine the net GHG emissions from landfilling each material, the net GHG emissions from CH_4 generation, carbon storage (treated as negative emissions), and transportation CO_2 emissions were summed. The results are shown in Exhibit 6-8. The four columns under section "e" of the exhibit may be used by local MSW planners to estimate GHG emissions from MSW in a given community.

As the exhibit shows, the postconsumer results for organic materials vary widely. For some materials—in particular newspaper and phonebooks—landfilling results in substantial negative net GHG emissions. For others—including office paper, textbooks, and food discards—net emissions are significant. For the rest, net emissions and reductions are relatively small.

Exhibit 6-6
GHG Emissions from CH_4 Generation

		CH_4 from Landfills Without CH_4 Recovery		CH_4 from Landfills With LFG Recovery and:						Percentage of CH_4 from Each Type of Landfill in 2003			Net CH_4 Generation	Avoided CO_2 from Energy Recovery	TOTAL
				Flaring		Electricity Generation									
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(l)	(m)	(n)	(o)	(p)	(q)
Material	CH_4 Generation (MTCE/Wet Ton)	CH_4 Not Oxidized to CO_2	Net GHG Emissions From CH_4 Generation (MTCE/Wet Ton)	CH_4 Not Recovered (100% Minus LFG Collection System Efficiency)	CH_4 Not Recovered That Is Not Oxidized to CO_2	Net GHG Emissions From CH_4 Generation (MTCE/Wet Ton)	Utility CO_2 Emissions Avoided per MTCE CH_4 Combusted (MTCE)	CH_4 Recovered for Electricity Generation Not Utilized Due to System "Down Time"	Utility CO_2 Emissions Avoided (MTCE/Wet Ton)	CH_4 From Landfills Without LFG Recovery in 2000	CH_4 From Landfills With LFG Recovery And Flaring in 2000	CH_4 From Landfills With LFG Recovery and Electricity Generation in 2000	Net CH_4 Emissions from Landfilling (MTCE/Wet Ton)	Net Avoided CO_2 Emissions from Landfilling (MTCE/Wet Ton)	Net GHG Emissions From Landfilling (MTCE/Wet Ton)
Corrugated Cardboard	0.688	90%	0.619	25%	90%	0.155	-0.153	0.150	-0.067	41%	28%	31%	0.344	-0.021	0.323
Magazines/Third-class Mail	0.278	90%	0.250	25%	90%	0.062	-0.153	0.150	-0.027	41%	28%	31%	0.139	-0.008	0.130
Newspaper	0.244	90%	0.220	25%	90%	0.055	-0.153	0.150	-0.024	41%	28%	31%	0.122	-0.007	0.115
Office Paper	1.198	90%	1.078	25%	90%	0.270	-0.153	0.150	-0.117	41%	28%	31%	0.599	-0.037	0.562
Phonebooks	0.244	90%	0.220	25%	90%	0.055	-0.153	0.150	-0.024	41%	28%	31%	0.122	-0.007	0.115
Textbooks	1.198	90%	1.078	25%	90%	0.270	-0.153	0.150	-0.117	41%	28%	31%	0.599	-0.037	0.562
Dimensional Lumber	0.355	90%	0.320	25%	90%	0.080	-0.153	0.150	-0.035	41%	28%	31%	0.178	-0.011	0.167
Medium-density Fiberboard	0.355	90%	0.320	25%	90%	0.080	-0.153	0.150	-0.035	41%	28%	31%	0.178	-0.011	0.167
Food Discards	0.445	90%	0.400	25%	90%	0.100	-0.153	0.150	-0.043	41%	28%	31%	0.222	-0.014	0.209
Yard Trimmings	0.264	90%	0.238	25%	90%	0.059	-0.153	0.150	-0.026	41%	28%	31%	0.132	-0.008	0.124
Grass	0.150	90%	0.135	25%	90%	0.034	-0.153	0.150	-0.015	41%	28%	31%	0.075	-0.005	0.070
Leaves	0.281	90%	0.253	25%	90%	0.063	-0.153	0.150	-0.027	41%	28%	31%	0.141	-0.009	0.132
Branches	0.355	90%	0.320	25%	90%	0.080	-0.153	0.150	-0.035	41%	28%	31%	0.178	-0.011	0.167
Mixed Paper[a]															
Broad Definition	0.651	90%	0.59	25%	90%	0.146	-0.153	0.150	-0.063	41%	28%	31%	0.325	-0.020	0.305
Residential Definition	0.616	90%	0.55	25%	90%	0.139	-0.153	0.150	-0.060	41%	28%	31%	0.308	-0.019	0.289
Office Paper Definition	0.641	90%	0.58	25%	90%	0.144	-0.153	0.150	-0.062	41%	28%	31%	0.321	-0.020	0.301
Mixed MSW	0.580	90%	0.522	25%	90%	0.131	-0.153	0.150	-0.056	41%	28%	31%	0.290	-0.018	0.272

[a] The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.

6.5 LIMITATIONS

Perhaps the most important caveat to the analysis of GHG emissions and storage associated with landfilling is that the results are based on a single set of laboratory experiments, those conducted by Dr. Morton Barlaz. Although researchers other than Dr. Barlaz have conducted laboratory studies that track the degradation of mixed MSW, his experiments were the only ones EPA identified that rigorously tested materials on an individual basis. Dr. Barlaz is recognized as an expert on the degradation of different fractions of MSW under anaerobic conditions, and his findings with respect to the CH_4 potential of mixed MSW are within the range used by landfill gas developers. Nevertheless, given the sensitivity of the landfill results to estimated CH_4 generation and carbon storage, EPA recognizes that more research is needed in this area.

Another important caveat relates to the estimate that 59 percent of MSW landfill CH_4 is generated at landfills with LFG recovery systems. The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate. Because of the high GWP of CH_4, small changes in the LFG recovery rate (for the national average landfill) could have a large effect on the net GHG impacts of landfilling each material and the ranking of landfilling relative to other MSW management options. The effects of different rates of LFG recovery are shown in Exhibit 6-9. Column "b" of the exhibit shows net GHG emissions if 20 percent of waste were disposed of at landfills with recovery. The remaining columns show net GHG emissions at increasing LFG recovery rates, up to a 60 percent rate. As the exhibit shows, the net postconsumer GHG emissions for landfilling mixed MSW decline significantly as recovery increases. At the local level, the GHG emissions from landfilling MSW depend on whether the local landfill has LFG recovery, as shown in Exhibit 6-8.

Because the national average estimate of emissions is based on estimated year 2003 LFG recovery levels, several limitations are associated with the use of this emission factor. First, because landfill CH_4 generation occurs over time and has significant timing delays (i.e., CH_4 generation may not begin until a few years after the waste is deposited in the landfill and can continue for many years after the landfill is closed), the values listed in this chapter represent total CH_4 generated, over time, per ton of waste landfilled. To the extent that LFG recovery rates shift dramatically over time, these shifts are not reflected in the analysis. Second, landfills with LFG recovery may be permitted, under EPA regulations, to remove the LFG recovery equipment when three conditions are met: (1) the landfill is permanently closed, (2) LFG has been collected continuously for at least 15 years, and (3) the landfill emits less than 50 metric tons of non-CH_4 organic compounds per year.[33] Although the removal of LFG recovery equipment will permit CH_4 from closed landfills to escape into the atmosphere, the amounts of CH_4 emitted should be relatively small, because of the length of time required for LFG collection before LFG recovery equipment is removed. Third, several methodological issues are associated with applying the CH_4 generation estimates from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (U.S. Inventory) to develop the national average emission factors: [34]

(1) The generation estimates in the U.S. Inventory include closed landfills (generation is modeled as a function of waste in place), whereas the estimates used in this report apply to ongoing generation (which is routed to open landfills);

(2) Likewise, both the flaring and landfill gas-to-energy estimates also include closed landfills; and

(3) The distribution of waste in place is not a perfect proxy for the destination of ongoing waste generation.

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[33] *Federal Register*, 1996, Vol. 61, No. 49, p. 9907.

[34] U.S. Department of State, 2002. *U.S. Climate Action Report—2002*. Washington DC, May.

CH_4 oxidation rate and landfill gas collection system efficiency are also important factors driving results. EPA used values of 10 percent and 75 percent, respectively, as best estimates for these factors. Reviewers of previous editions of this report and sources in the literature have reported estimates ranging from about 5 percent to 40 percent for oxidation, and from about 60 to 95 percent for collection system efficiency. EPA investigated the sensitivity of the results to these assumptions, and the results are shown in Exhibit 6-10. To portray the sensitivity as a bounding analysis, EPA used the combinations of variables yielding the upper bound emission factor (5 percent oxidation, 60 percent collection efficiency) and the lower bound (40 percent oxidation, 95 percent efficiency).[35] As the exhibit shows, the materials most sensitive to these variables are those with the highest CH_4 generation potential, i.e., corrugated cardboard, office paper, textbooks, food discards, and mixed paper. Sensitivity varies: the difference between upper and lower bounds ranges from 0.05 MTCE/ton for grass to 0.42 MTCE/ton for office paper and textbooks. The postconsumer emission factors of several materials and mixed material combinations—corrugated cardboard, grass, mixed paper, and mixed MSW—change from having net storage under the lower bound to having net emissions under the upper bound.

Ongoing shifts in the use of landfill cover and liner systems are likely to influence the rate of CH_4 generation and collection. As more landfills install effective covers and implement controls to keep water and other liquids out, conditions will be less favorable for degradation of organic wastes. Over the long term, these improvements may result in a decrease in CH_4 generation and an increase in carbon storage. Moreover, Dr. Barlaz believes that the CH_4 yields from his laboratory experiments are likely to be higher than CH_4 yields in a landfill, because the laboratory experiments were designed to generate the maximum amount of CH_4 possible. If the CH_4 yields from the laboratory experiments were higher than yields in a landfill, the net GHG emissions from landfilling organic materials would be lower than estimated here.

EPA assumed that once wastes are disposed in a landfill, they are never removed. In other words, it was assumed that landfills are never "mined." A number of communities have mined their landfills—removing and combusting the waste—in order to create more space for continued disposal of waste in the landfill. To the extent that landfills are mined in the future, it is incorrect to assume that carbon stored in a landfill will remain stored. For example, if landfilled wastes are later combusted, the carbon that was stored in the landfill will be oxidized to CO_2 in the combustor.

The estimate of avoided utility GHG emissions per unit of CH_4 combusted assumes that all landfill gas-to-energy projects are electricity producing. In reality, some projects are "direct gas" projects, in which CH_4 is piped directly to the end user for use as fuel. In these cases, the CH_4 typically replaces natural gas as a fuel source. Because natural gas use is less GHG-intensive than average electricity production, direct gas projects will tend to offset fewer GHG emissions than electricity projects will—a fact not reflected in the analysis.

For landfilling of yard trimmings (and other organic materials), EPA assumed that all carbon storage in a landfill environment is incremental to the storage that occurs in a nonlandfill environment. In other words, it was assumed that in a baseline where yard trimmings are returned to the soil (i.e., in a nonlandfill environment), all of the carbon is decomposed relatively rapidly (i.e., within several years) to CO_2, and there is no long-term carbon storage. To the extent that long-term carbon storage occurs in the baseline, the estimates of carbon storage reported here are overstated, and the net postconsumer GHG emissions are understated.

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[35] Exhibit 6-10 also reports two intermediate combinations, including the best estimate values.

Finally, the analysis is limited by the assumptions that were made at various steps in the analysis, as described throughout this chapter. The key assumptions that have not already been discussed as limitations are the assumptions used in developing "corrected" CH_4 yields for organic materials in MSW. Because of the high GWP of CH_4, a small difference between estimated and actual CH_4 generation values would have a large effect on the GHG impacts of landfilling and the ranking of landfilling relative to other MSW management options.

Exhibit 6-7
Calculation to Estimate Utility GHGs Avoided through Combustion of Landfill CH_4

Step	Value	Source
Metric tons CH_4/MTCE CH_4	0.17	1/((12/44) × Global warming potential of CH_4)
Grams CH_4/metric ton CH_4	1.00E+06	Physical constant
Cubic ft. CH_4/gram CH_4	0.05	1/20: 20 grams per cubic foot of CH_4 at standard temperature and pressure
Btu/cubic ft. CH_4	1,012	EPA 2005. LMOP Benefits Calculator.
kWh electricity generated/Btu	0.00009	1/11,700: EPA 2005. LMOP Benefits Calculator.
Electricity generation efficiency	0.85	EPA 2005. LMOP Net capacity factor for generation units (availability, operating load, parasitic losses).
Kg utility C avoided/kWh generated electricity	2.405E-01	0.24 kg CE/kWh generated electricity, from Exhibit 5-4. This assumes that LFG energy recovery displaces fossil fuel generation.
Metric tons avoided utility C/kg utility C	0.001	1000 kg per metric ton
Ratio of MTCE avoided utility C per MTCE CH_4	0.15	Product from multiplying all factors

Exhibit 6-8
Net GHG Emissions from Landfilling[a]

(a)	(b) Net GHG Emissions from CH_4 Generation (MTCE/Wet Ton)				(c)	(d)	(e) (= b + c + d) Net GHG Emissions from Landfilling (MTCE/Wet Ton)			
Material	Landfills Without LFG Recovery	Landfills With LFG Recovery And Flaring	Landfills With LFG Recovery And Electric Generation	Year 2003 National Average	Net Carbon Storage (MTCE/Wet Ton)	GHG Emissions From Transportation (MTCE/Wet Ton)	Landfills Without LFG Recovery	Landfills With LFG Recovery And Flaring	Landfills With LFG Recovery And Electric Generation	Year 2003 National Average
Aluminum Cans	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Steel Cans	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Copper Wire	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Glass	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
HDPE	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
LDPE	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
PET	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Corrugated Cardboard	0.62	0.15	0.09	0.32	-0.22	0.01	0.41	-0.06	-0.13	0.11
Magazines/Third-class Mail	0.25	0.06	0.04	0.13	-0.22	0.01	0.04	-0.15	-0.18	-0.08
Newspaper	0.22	0.05	0.03	0.11	-0.36	0.01	-0.13	-0.30	-0.32	-0.24
Office Paper	1.08	0.27	0.15	0.56	-0.04	0.01	1.05	0.24	0.12	0.53
Phonebooks	0.22	0.05	0.03	0.11	-0.36	0.01	-0.13	-0.30	-0.32	-0.24
Textbooks	1.08	0.27	0.15	0.56	-0.04	0.01	1.05	0.24	0.12	0.53
Dimensional Lumber	0.32	0.08	0.05	0.17	-0.31	0.01	0.02	-0.22	-0.25	-0.13
Medium-density Fiberboard	0.32	0.08	0.05	0.17	-0.31	0.01	0.02	-0.22	-0.25	-0.13
Food Discards	0.40	0.10	0.06	0.21	-0.02	0.01	0.39	0.09	0.05	0.20
Yard Trimmings	0.24	0.06	0.03	0.12	-0.19	0.01	0.05	-0.12	-0.15	-0.06
Grass	0.14	0.03	0.02	0.07	-0.08	0.01	0.06	-0.04	-0.05	0.00
Leaves	0.25	0.06	0.04	0.13	-0.19	0.01	0.07	-0.12	-0.14	-0.05
Branches	0.32	0.08	0.05	0.17	-0.31	0.01	0.02	-0.22	-0.25	-0.13
Mixed Paper[b]										
Broad Definition	0.59	0.15	0.08	0.31	-0.22	0.01	0.38	-0.06	-0.13	0.09
Residential Definition	0.55	0.14	0.08	0.29	-0.23	0.01	0.33	-0.08	-0.14	0.07
Office Paper Definition	0.58	0.14	0.08	0.30	-0.18	0.01	0.40	-0.03	-0.09	0.13
Mixed MSW	0.52	0.13	0.07	0.27	-0.17	0.01	0.37	-0.03	-0.08	0.12
Carpet	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Personal Computers	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Clay Bricks	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Concrete	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Fly Ash	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Tires	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01

Explanatory Notes:

[a] Please see Exhibit 6-6 for details on calculations.

[b] The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.

Exhibit 6-9
Net GHG Emissions from CH_4 Generation at Landfills with Recovery (MTCE/Wet Ton)

Sensitivity Analysis: Varying the Percentage of Waste Disposed at Landfills with CH_4 Recovery					
(a)	(b)	(c)	(d)	(e)	(f)
Material	**17%**	**20%**	**49%**	**55%**	**60%**
Corrugated Cardboard	0.32	0.30	0.15	0.12	0.09
Magazines/Third-class Mail	0.00	0.00	-0.07	-0.08	-0.09
Newspaper	-0.16	-0.17	-0.22	-0.23	-0.24
Office Paper	0.89	0.86	0.60	0.54	0.50
Phonebooks	-0.16	-0.17	-0.22	-0.23	-0.24
Textbooks	0.89	0.86	0.60	0.54	0.50
Dimensional Lumber	-0.03	-0.03	-0.11	-0.13	-0.14
Medium-density Fiberboard	-0.03	-0.03	-0.11	-0.13	-0.14
Food Discards	0.33	0.32	0.22	0.20	0.19
Yard Trimmings	0.02	0.01	-0.04	-0.06	-0.07
Grass	0.04	0.04	0.01	0.00	-0.01
Leaves	0.04	0.03	-0.03	-0.05	-0.06
Branches	-0.03	-0.03	-0.11	-0.13	-0.14
Mixed Paper[a]					
Broad Definition	0.29	0.28	0.13	0.10	0.08
Residential Definition	0.25	0.24	0.10	0.08	0.05
Office Paper Definition	0.32	0.31	0.16	0.13	0.11
Mixed MSW	0.29	0.28	0.15	0.12	0.10

[a] The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.

Exhibit 6-10
Net GHG Emissions from CH_4 Generation at Landfills with Recovery (MTCE/Wet Ton)

Sensitivity Analysis: Varying Oxidation and Gas Collection Efficiency Rates.				
Oxidation Rate:	**40%**	**25%**	**10%**	**5%**
Collection Efficiency:	**95%**	**85%**	**75%**	**60%**
Material	**Lower-bound Emissions**	**Conservative (High) Emissions**	**Best Estimate**	**Upper-bound Emissions**
Corrugated Cardboard	0.18	0.26	0.34	0.42
Magazines/Third-class Mail	0.07	0.10	0.14	0.17
Newspaper	0.06	0.09	0.12	0.15
Office Paper	0.31	0.45	0.60	0.73
Phonebooks	0.06	0.09	0.12	0.15
Textbooks	0.31	0.45	0.60	0.73
Dimensional Lumber	0.09	0.13	0.18	0.22
Medium-density Fiberboard	0.09	0.13	0.18	0.22
Food Discards	0.12	0.17	0.22	0.27
Yard Trimmings	0.07	0.10	0.13	0.16
Grass	0.04	0.06	0.08	0.09
Leaves	0.07	0.10	0.14	0.17
Branches	0.09	0.13	0.18	0.22
Mixed Paper [a]				
Broad Definition	0.17	0.24	0.33	0.40
Residential Definition	0.16	0.23	0.31	0.38
Office Paper Definition	0.17	0.24	0.32	0.39
Mixed MSW	0.15	0.22	0.29	0.36

[a] The summary values for mixed paper are based on the proportions of the four paper types (corrugated cardboard, magazines/third-class mail, newspaper, and office paper) that constitute the different "mixed paper" definitions.

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7. ENERGY IMPACTS

The previous chapters of this report were focused on life-cycle GHG emissions associated with each of five management options for MSW. Materials have energy impacts at each life-cycle stage; the stages addressed in this report include the acquisition of raw materials, the manufacture of raw materials into products, and product disposal or recovery. Waste *reduction* practices (source reduction, recycling, and reuse) reduce the demand for raw material and energy inputs to the manufacturing stage of the life cycle, thereby conserving energy and reducing GHG emissions. Energy savings can also result from some waste *disposal* practices, including waste-to-energy combustors and landfill gas-to-energy systems.

To better understand the relationship between materials management and energy use, energy factors were developed for four waste management practices (source reduction, recycling, combustion, and landfilling), and this chapter includes a discussion on how to use these energy factors and the relationship between energy savings and GHG benefits.

7.1 METHODOLOGY FOR DEVELOPING ENERGY FACTORS

The methodology used to develop these emission factors is fundamentally the same as described in the preceding chapters, except that here the researchers view all life-cycle components through the lens of energy consumption or savings, rather than GHG emissions. Components such as forest carbon sequestration and landfill carbon storage are not a part of the energy life cycle; therefore they are not described here. The energy factors are based primarily on the amount of energy required to produce 1 ton of a given material. The total energy consumed is a result of direct fossil fuel and electricity consumption associated with raw material acquisition and manufacturing; fossil fuel consumption for transportation; and embedded energy. The total process and transportation energy for the production of both virgin and recycled materials is shown in Exhibits 2-3 to 2-7. Although the GHG emission factors are a product of fuel mix and the carbon coefficients of fuels, the energy factors are based only on the energy consumption (direct fossil fuel and electricity) component and are left in terms of Btu of energy consumption. Therefore, the total process energy required to make 1 ton of a particular material is the sum of energy consumed across all of the fuel types.

The total energy, or embodied energy, required to manufacture each material is made up of two components: (1) process and transportation energy, and (2) embedded energy (i.e., energy of the raw material). The process and transportation components are conceptually straightforward, but embedded energy is more complex. Embedded energy is the energy contained within the raw materials used to manufacture a product. For example, the embedded energy of plastics is due to their being made from petroleum. Because petroleum has an inherent energy value, the amount of energy that is saved through plastic recycling and source reduction is directly related to the energy that could have been produced if the petroleum had been used as an energy source rather than as a raw material input. Aluminum is the other material in this analysis that includes an embedded energy component. The aluminum smelting process requires a carbon anode, which is consumed during the electrolytic reduction process; carbon anodes are made from coal, itself an energy source. Total energy values contained in this report also include both nonrenewable and renewable sources. For example, the total energy savings estimate for recycling paper includes some renewable energy fuel sources that may have little or no associated GHG emissions.

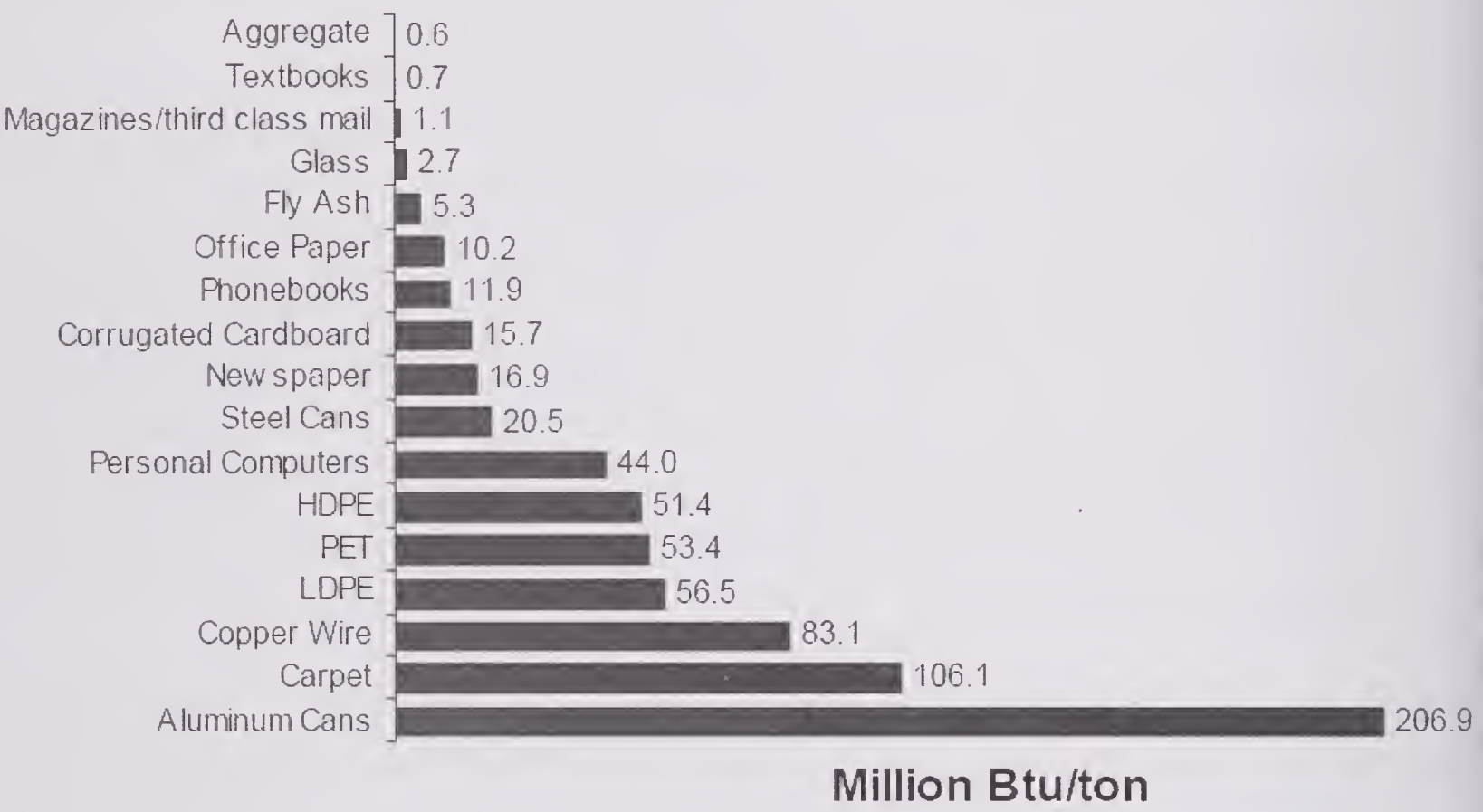
7.2 ENERGY IMPLICATIONS FOR WASTE MANAGEMENT OPTIONS

This chapter presents the life-cycle energy implications for four waste management practices. As with the GHG emission factors already presented, negative values indicate net energy savings.

Waste reduction efforts such as source reduction and recycling can result in significant energy savings. Source reduction techniques such as double-sided copying and light-weighting are in most cases more effective at reducing energy than recycling. This is because source reduction significantly reduces energy consumption associated with raw material extraction and manufacturing processes.

When comparing recycling to landfill disposal, aluminum cans give the greatest energy savings per ton, as shown in Exhibit 7-1. These savings reflect the nature of aluminum production; manufacturing aluminum cans from virgin inputs is very energy intensive, whereas relatively little energy is required to manufacture cans from recycled aluminum. Recycling carpet also results in significant energy savings, since the recycled material is turned into secondary products and the energy-intensive processes that would have been used to manufacture those secondary products are avoided.

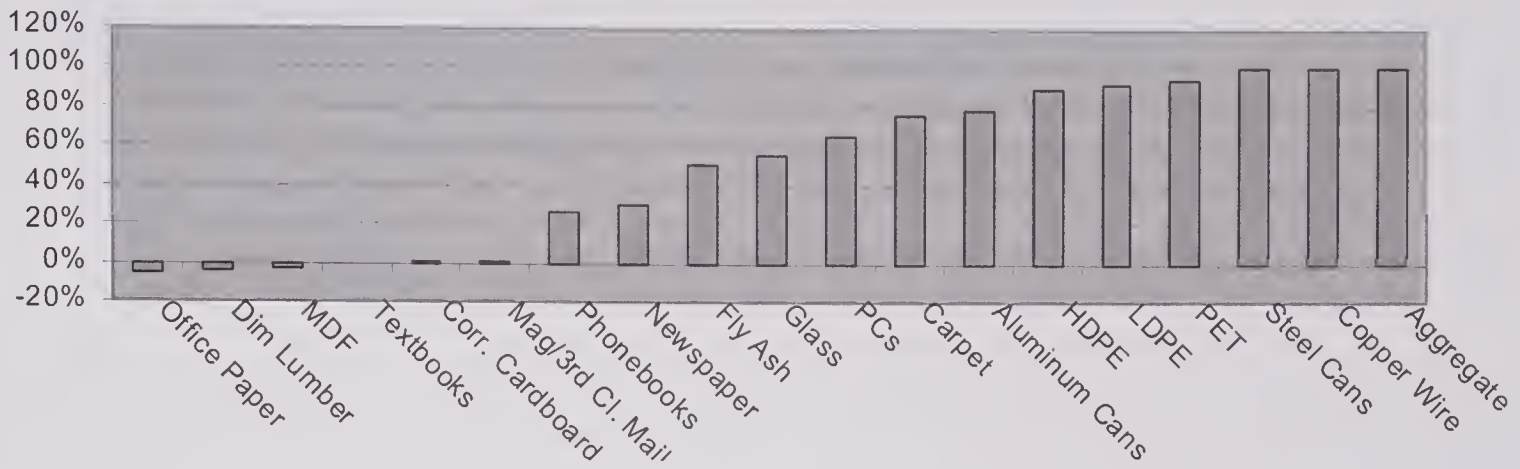
Exhibit 7-1 Energy Savings per Ton Recycled [a]



[a] Assumes recycled materials would otherwise have been landfilled. Aggregate refers to concrete recycled as aggregate.

Some materials, such as dimensional lumber and medium-density fiberboard, actually use more energy when they are made from recycled inputs. For these materials, the recovery and processing of recycled material is more energy intensive than making the material from virgin inputs. Although these materials may not provide an energy benefit from recycling, from a GHG emissions perspective, recycling these materials is still beneficial. Exhibit 7-2 presents the GHG benefits attributable to the energy savings achieved through recycling.

Exhibit 7-2 Recycling GHG Benefits Attributable to Energy Savings (Recycling vs. Landfilling)



7.3 APPLYING ENERGY FACTORS

Due to recent fuel shortages and increases in prices for fuel and energy, it is becoming increasingly important to examine the impacts of waste management practices on energy. The energy factors presented in Exhibit 7-3 through Exhibit 7-8 may be used by organizations interested in quantifying energy savings associated with waste management practices. With these exhibits, organizations can compare the energy benefits of switching from landfilling to one of the other waste management options. For example, using these factors, the researchers evaluated the progress of voluntary programs aimed at source reduction and recycling, such as EPA's WasteWise, Pay-as-You-Throw, and Coal Combustion Product Partnership (C^2P^2) programs.

In order to apply the energy factors presented in this report, one must first establish two scenarios: (1) a baseline scenario that represents current management practices (e.g., disposing of 1 ton of steel cans in a landfill); and (2) an alternative scenario that represents the alternative management practice (e.g., recycling the same ton of steel cans).[1] The energy factors developed in this report can then be used to calculate energy consumed or avoided under both the baseline and the alternative management practices. Once energy for the two scenarios has been determined, the next step is to calculate the difference between the alternative scenario and the baseline scenario. The result represents the energy consumed or avoided that is attributable to the alternative waste management practice.

Exhibit 7-8 illustrates the application of these factors where the baseline management scenario is disposal in a landfill with national average conditions. In the alternate scenario, the material is recycled. For example, recycling 1 ton of steel cans rather than landfilling them reduces the energy consumed by 20.5 million Btu. The calculations used to generate this result are shown below. Under the sign convention used in this report, the negative value indicates that energy consumption is avoided.

Energy Impacts of Waste Reduction

Baseline: landfill 1 ton of steel cans
1 ton x 0.53 million Btu/ton = 0.53 million Btu

Alternate: recycle 1 ton of steel cans
1 ton x -19.97 million Btu/ton = -19.97 million Btu

Energy Savings:
-19.97 million Btu – 0.53 million Btu =
- 20.5 million Btu

[1] The energy factors are expressed in terms of million Btu of energy per ton of material managed. In the case of recycling, EPA defines 1 ton of material managed as 1 ton *collected* for recycling.

In cases where parties have been source reducing or recycling materials not specifically analyzed in this report, it is possible to estimate the energy consumed or avoided by assigning surrogate materials. A list of materials not specifically analyzed and their corresponding surrogates is presented in the following chapter. Surrogates are based on similarities in characteristics likely to drive energy factors, such as similarities in energy consumption during the raw material acquisition and manufacturing life-cycle stages. Note that the use of these surrogates involves considerable uncertainty.

7.4 RELATING ENERGY SAVINGS TO GHG BENEFITS

It can be difficult to conceptualize energy savings in Btu and GHG emissions reductions in MTCE; therefore, these quantities are frequently converted to common equivalents such as barrels of crude oil or gallons of gasoline. There are important nuances to interpreting these equivalencies, particularly converting from savings in MTCE to equivalent energy savings. This is complicated for two reasons: (1) GHG reductions reflect both energy and nonenergy savings, and (2) the energy savings reflect savings across a range of fossil fuels. Thus, converting from total GHG reductions to an equivalency for "barrels of oil" must be done with caution.

Common Energy Conversion Factors

Fuel:	Million Btu per Barrel of Oil: 5.8 Gallons Oil per Barrel of Oil: 42 Million Btu per Gallon of Gas: 0.125
Cars ("average" passenger car over one year):	Fuel Consumption (gallons of gas): 502 CO_2 Emissions (tons): 4.6

Although energy savings are often the driving force behind GHG emissions savings, it would not be accurate to directly convert overall GHG emission benefits into energy savings equivalents. Equivalencies must remain consistent within the energy or GHG emission context in which they were originally created. As shown in Exhibit 7-2, energy consumption can account for only a fraction of the emission benefits associated with some material types. For example, only about 55 percent of the emission benefits for recycling glass are due to energy consumption. Because the GHG benefits of glass recycling consist of some energy and some nonenergy-related savings, this material type demonstrates the difficulties of converting GHG savings to energy equivalents. When the total GHG benefits of recycling glass are converted to barrels of oil using the common equivalency factors, the *GHG emission benefits* are equivalent to GHG emissions from the combustion of 68 barrels of oil. In contrast, the *energy savings* associated with recycling glass are equivalent to the energy content of 46 barrels of oil.

Recycling 100 tons of Glass Compared to Landfilling

GHG Emission Benefits: 9 MTCE

Equivalent to the combustion emissions from *68* barrels of oil.

Energy Savings: 265 Million Btu

Equivalent to the energy contained within *46* barrels of oil.

Understanding the differences between these values is very important. Similarly, because energy savings estimates are based on a diverse fuel mix of fuels (electricity, natural gas, petroleum, coal, etc.), the results do not mean that 46 barrels of oil will be avoided in the real world. The equivalency "barrels of oil" is simply utilized as a recognizable and understandable unit of energy. In the case of manufacturing glass, the primary energy sources are electricity, coal, and natural gas with only a small fraction of the total energy derived from petroleum products.

Exhibit 7-3
Energy Consumed/Avoided for Source Reduction (Million Btu/Ton of Material Source Reduced)

Material	(a) Raw Materials Acquisition and Manufacturing Process Energy		(b) Raw Materials Acquisition and Manufacturing Transport Energy		(d) Net Energy (d = a + b)	
	Source Reduction Displaces Current Mix of Virgin and Recycled Inputs	Source Reduction Displaces Virgin Inputs	Source Reduction Displaces Current Mix of Virgin and Recycled Inputs	Source Reduction Displaces Virgin Inputs	Source Reduction Displaces Current Mix of Virgin and Recycled Inputs	Source Reduction Displaces Virgin Inputs
Aluminum Cans	121.85	231.42	4.33	7.46	126.18	238.88
Steel Cans	26.04	31.58	4.75	4.91	30.79	36.49
Copper Wire	121.45	122.52	0.86	0.77	122.31	123.30
Glass	5.99	6.49	1.54	1.60	7.53	8.09
HDPE	63.19	69.75	0.49	0.48	63.68	70.23
LDPE	73.43	76.32	0.49	0.48	73.92	76.80
PET	70.19	72.23	0.49	0.48	70.67	72.71
Corrugated Cardboard	20.45	25.13	1.45	1.63	21.91	26.76
Magazines/Third-class Mail	32.95	32.99	0.26	0.26	33.21	33.25
Newspaper	35.80	39.92	0.65	0.76	36.45	40.68
Office Paper	36.32	37.01	0.26	0.26	36.58	37.27
Phonebooks	39.61	39.61	0.26	0.26	39.87	39.87
Textbooks	35.01	35.07	0.29	0.26	35.30	35.33
Dimensional Lumber	2.53	2.53	1.00	1.00	3.53	3.53
Medium-density Fiberboard	10.18	10.18	1.33	1.33	11.51	11.51
Food Discards	NA	NA	NA	NA	NA	NA
Yard Trimmings	NA	NA	NA	NA	NA	NA
Mixed Paper						
Broad Definition	27.16	32.26	1.42	1.79	27.16	32.26
Residential Definition	26.86	32.26	1.40	1.79	26.86	32.26
Office Paper Definition	71.35	73.44	1.91	2.07	71.35	73.44
Mixed Metals	NA	NA	NA	NA	NA	NA
Mixed Plastics	NA	NA	NA	NA	NA	NA
Mixed Recyclables	NA	NA	NA	NA	NA	NA
Mixed Organics	NA	NA	NA	NA	NA	NA
Mixed MSW (as disposed)	NA	NA	NA	NA	NA	NA
Carpet	89.70	89.70	1.36	1.36	91.06	91.06
Personal Computers	951.71	951.71	5.03	5.03	956.74	956.74
Clay Bricks	5.10	5.10	0.03	0.03	5.13	5.13
Concrete	NA	0.05	NA	0.19	NA	0.05
Fly Ash	4.77	4.77	0.10	0.10	4.77	4.77
Tires	88.17	88.17	NA	NA	88.17	88.17

Exhibit 7-4
Energy Consumed/Avoided for Recycling (Million Btu/Ton of Material Recycled)

Material	(a) Recycled Input Credit Process Energy	(b) Recycled Input Credit Transportation Energy	(c) Net Consumption/Savings (Postconsumer)
Aluminum Cans	-200.68	-5.74	-206.42
Steel Cans	-19.40	-0.56	-19.97
Copper Wire	-81.64	-0.95	-82.59
Glass	-1.91	-0.21	-2.13
HDPE	-50.97	0.06	-50.90
LDPE	-56.07	0.06	-56.01
PET	-52.90	0.06	-52.83
Corrugated Cardboard	-14.67	-0.74	-15.42
Magazines/Third-class Mail	-0.69	0.00	-0.69
Newspaper	-16.07	-0.42	-16.49
Office Paper	-10.08	0.00	-10.08
Phonebooks	-11.93	0.51	-11.42
Textbooks	-1.03	0.50	-0.53
Dimensional Lumber	0.52	0.07	0.59
Medium-density Fiberboard	0.65	0.21	0.86
Food Discards	NA	0.58	0.58
Yard Trimmings	NA	0.58	0.58
Mixed Paper			
Broad Definition	-21.38	-1.57	-22.94
Residential Definition	-21.38	-1.57	-22.94
Office Paper Definition	-12.98	-0.97	-13.95
Mixed Metal	-72.72	-2.08	-74.81
Mixed Plastics	-52.48	0.06	-52.42
Mixed Recyclables	-16.36	-0.55	-16.91
Mixed Organics	NA	0.58	0.58
Mixed MSW (as disposed)	NA	NA	NA
Carpet	-103.67	-1.90	-105.58
Personal Computers	-41.95	-1.48	-43.44
Clay Bricks	NA	NA	NA
Concrete	-0.01	-0.09	-0.11
Fly Ash	-4.77	0.00	-4.77
Tires[a]	-51.96	0.00	-51.96

[a] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

Exhibit 7-5
Energy Consumed/Avoided for Combustion (Million Btu/Ton of Material Combusted)

Material	Avoided Utility Fuel Consumption	Energy Savings Due to Steel Recovery	Transportation to Combustion Facility	Net Consumption/ Savings (Postconsumer)
Aluminum Cans	0.12	NA	0.30	0.42
Steel Cans	0.07	-17.61	0.30	-17.24
Copper Wire	0.10	NA	0.30	0.39
Glass	0.08	NA	0.30	0.38
HDPE	-6.66	NA	0.30	-6.37
LDPE	-6.66	NA	0.30	-6.37
PET	-3.46	NA	0.30	-3.16
Corrugated Cardboard	-2.51	NA	0.30	-2.21
Magazines/Third-class Mail	-1.87	NA	0.30	-1.58
Newspaper	-2.83	NA	0.30	-2.54
Office Paper	-2.42	NA	0.30	-2.13
Phonebooks	-2.83	NA	0.30	-2.54
Textbooks	-2.42	NA	0.30	-2.13
Dimensional Lumber	-2.96	NA	0.30	-2.66
Medium-density Fiberboard	-2.96	NA	0.30	-2.66
Food Discards	-0.85	NA	0.30	-0.55
Yard Trimmings	-1.00	NA	0.30	-0.70
Mixed Paper				
Broad Definition	-2.52	NA	0.30	-2.22
Residential Definition	-2.51	NA	0.30	-2.21
Office Paper Definition	-2.32	NA	0.30	-2.02
Mixed Metals	0.09	-12.43	0.30	-12.05
Mixed Plastics	-5.39	NA	0.30	-5.09
Mixed Recyclables	-2.36	-0.61	0.30	-2.67
Mixed Organics	-0.88	NA	0.30	-0.58
Mixed MSW (as disposed)	-1.78	NA	0.30	-1.49
Carpet	-4.78	NA	0.30	-4.78
Personal Computers	-0.55	-4.44	0.30	-4.69
Clay Bricks	NA	NA	NA	NA
Concrete	NA	NA	NA	NA
Fly Ash	NA	NA	NA	NA
Tires	-25.95	-1.06	0.30	-26.71

Exhibit 7-6
Energy Consumed/Avoided for Landfilling (Million Btu/Ton of Material Landfilled)

Material	Transportation to Landfill	Avoided Utility Energy	Net Consumption/ Savings (Postconsumer)
Aluminum Cans	0.53	NA	0.53
Steel Cans	0.53	NA	0.53
Copper Wire	0.53	NA	0.53
Glass	0.53	NA	0.53
HDPE	0.53	NA	0.53
LDPE	0.53	NA	0.53
PET	0.53	NA	0.53
Corrugated Cardboard	0.53	(0.30)	0.23
Magazines/Third-class Mail	0.53	(0.12)	0.41
Newspaper	0.53	(0.11)	0.42
Office Paper	0.53	(0.52)	0.01
Phonebooks	0.53	(0.11)	0.42
Textbooks	0.53	(0.52)	0.01
Dimensional Lumber	0.53	(0.15)	0.37
Medium-density Fiberboard	0.53	(0.15)	0.37
Food Discards	0.53	(0.19)	0.33
Yard Trimmings	0.53	(0.11)	0.41
Mixed Paper			
Broad Definition	0.53	(0.28)	0.24
Residential Definition	0.53	(0.27)	0.26
Office Paper Definition	0.53	(0.28)	0.25
Mixed Metals	0.53	NA	0.53
Mixed Plastics	0.53	NA	0.53
Mixed Recyclables	0.53	(0.22)	0.30
Mixed Organics	0.53	(0.15)	0.37
Mixed MSW (as disposed)	0.53	(0.25)	0.28
Carpet	0.53	NA	0.53
Personal Computers	0.53	NA	0.53
Clay Bricks	0.53	NA	0.53
Concrete	0.53	NA	0.53
Fly Ash	0.53	NA	0.53
Tires	0.53	NA	0.53

Exhibit 7-7
Net Energy Consumed/Avoided from Source Reduction and MSW Management Options
(Million Btu/Ton)

Material	Source Reduction	Recycling	Combustion	Landfilling
Aluminum Cans	-126.18	-206.42	0.42	0.53
Steel Cans	-30.79	-19.97	-17.24	0.53
Copper Wire	-122.31	-82.59	0.39	0.53
Glass	-7.53	-2.13	0.38	0.53
HDPE	-63.68	-50.90	-6.37	0.53
LDPE	-73.92	-56.01	-6.37	0.53
PET	-70.67	-52.83	-3.16	0.53
Corrugated Cardboard	-21.91	-15.42	-2.21	0.23
Magazines/Third-class Mail	-33.21	-0.69	-1.58	0.41
Newspaper	-36.45	-16.49	-2.54	0.42
Office Paper	-36.58	-10.08	-2.13	0.01
Phonebooks	-39.87	-11.42	-2.54	0.42
Textbooks	-35.30	-0.53	-2.13	0.01
Dimensional Lumber	-3.53	0.59	-2.66	0.37
Medium-density Fiberboard	-11.51	0.86	-2.66	0.37
Food Discards	NA	0.58	-0.55	0.33
Yard Trimmings	NA	0.58	-0.70	0.41
Mixed Paper				
Broad Definition	NA	-22.94	-2.22	0.24
Residential Definition	NA	-22.94	-2.21	0.26
Office Paper Definition	NA	-13.95	-2.02	0.25
Mixed Metals	NA	-74.81	-12.05	0.53
Mixed Plastics	NA	-52.42	-5.09	0.53
Mixed Recyclables	NA	-16.91	-2.67	0.30
Mixed Organics	NA	0.58	-0.58	0.37
Mixed MSW (as disposed)	NA	NA	-1.49	0.28
Carpet	-91.06	-105.58	-4.78	0.53
Personal Computers	-956.74	-43.44	-4.69	0.53
Clay Bricks	-5.13	NA	NA	0.53
Concrete	NA	-0.11	NA	0.53
Fly Ash	NA	-4.77	NA	0.53
Tires	-88.17	-51.96[a]	-26.71	0.53

[a] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

Exhibit 7-8
Energy Consumed/Avoided for MSW Management Options Compared to Landfilling
(Million Btu/Ton)

Material	Source Reduction Net Energy Minus Landfilling Net Energy (Current Mix)	Source Reduction Net Energy Minus Landfilling Net Energy (100% Virgin Inputs)	Recycling Net Energy Minus Landfilling Net Energy	Combustion Net Energy Minus Landfilling Net Energy
Aluminum Cans	-126.71	-239.41	-206.95	-0.11
Steel Cans	-31.32	-37.02	-20.49	-17.77
Copper Wire	-122.84	-123.82	-83.12	-0.13
Glass	-8.06	-8.62	-2.65	-0.15
HDPE	-64.21	-70.76	-51.43	-6.89
LDPE	-74.45	-77.33	-56.54	-6.89
PET	-71.20	-73.24	-53.36	-3.69
Corrugated Cardboard	-22.13	-26.99	-15.65	-2.44
Magazines/Third-class Mail	-33.62	-33.66	-1.09	-1.98
Newspaper	-36.87	-41.10	-16.91	-2.96
Office Paper	-36.59	-37.28	-10.09	-2.14
Phonebooks	-40.29	-40.29	-11.84	-2.96
Textbooks	-35.31	-35.34	-0.54	-2.14
Dimensional Lumber	-3.90	-3.90	0.21	-3.04
Medium-density Fiberboard	-11.88	-11.88	0.49	-3.04
Food Discards	NA	NA	0.25	-0.88
Yard Trimmings	NA	NA	0.17	-1.11
Mixed Paper				
Broad Definition	NA	NA	-23.19	-2.47
Residential Definition	NA	NA	-23.20	-2.47
Office Paper Definition	NA	NA	-14.20	-2.27
Mixed Metals	NA	NA	-75.33	-12.57
Mixed Plastics	NA	NA	-52.94	-5.62
Mixed Recyclables	NA	NA	-17.21	-2.97
Mixed Organics	NA	NA	0.21	-0.93
Mixed MSW (as disposed)	NA	NA	-0.28	-1.76
Carpet	-91.59	-91.59	-106.11	-5.31
Personal Computers	-957.27	-957.27	-43.96	-5.22
Clay Bricks	-5.66	-5.66	NA	NA
Concrete	NA	NA	-0.63	NA
Fly Ash	NA	NA	-5.29	NA
Tires	-88.70	-88.70	-52.49[a]	-27.23

[a] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

8. ENERGY AND EMISSION BENEFITS

Earlier chapters of this report examined the energy implications and GHG emissions from each of five waste management options. This chapter summarizes the GHG emission factors for each option, explains the analytic framework for applying emission factors, reviews tools that can be used to evaluate GHG emissions from waste management practices, and describes opportunities for GHG emission reductions. The full discussion of the energy implications of waste management options, and tables showing the associated energy savings, are presented in Chapter 7. Readers are referred to Chapter 7 for complete explanation of energy impacts, or for help applying energy factors to a particular waste management option.

In the discussion that follows, the focus is on national average conditions. For example, landfills are represented as having the national average landfill gas recovery systems, and combustors are represented based on mass burn units with the national average system efficiency for collection of ferrous metal. As shown in the previous chapters, GHG emissions are sensitive to site-specific variables; emissions can and do differ from the national average scenario presented here. To allow customization of emission factors that better reflect site-specific conditions, EPA has developed three accounting tools: the WAste Reduction Model (WARM), which enables users to input several key variables (e.g., information on landfill gas collection systems, transportation distances) to assess the GHG and energy implications of waste management options; the Recycled Content (ReCon) Tool, which enables consumers and producers to assess the energy and GHG impacts of buying or producing goods with varying percentages of recycled content; and the Durable Goods Calculator, which assesses the energy and GHG impacts of recycling goods such as refrigerators and washing machines. EPA encourages readers to take advantage of these models when assessing their waste management options. The tools are described in further detail in Section 8.3 below.

8.1 NET GHG EMISSIONS FOR EACH WASTE MANAGEMENT OPTION

The net life-cycle GHG emissions for each waste management option for each material considered are shown in 8 exhibits that summarize the GHG emissions and sinks in MTCE/ton, which are described in detail in earlier chapters. In these exhibits, emission factors are shown for mixed plastics, mixed recyclables, and mixed organics. EPA developed the emission factor for mixed recyclables by calculating the average (weighted by tons recycled in 2003) of emission factors for aluminum cans, steel cans, glass, HDPE, LDPE, PET, corrugated cardboard, magazines/third-class mail, newspaper, office paper, phonebooks, textbooks, medium-density fiberboard, and dimensional lumber. The emission factor for mixed plastics is the average (weighted by tons recycled in 2003) of emission factors for HDPE, LDPE, and PET. The mixed organics emission factor is the average (weighted by tons composted in 2003) of emission factors for yard trimmings and food discards.[1]

As mentioned in Chapter 1, EPA used a waste generation reference point for measuring GHG emissions (i.e., GHG emissions were accounted for at the point of waste generation). All subsequent emissions and sinks from waste management practices are counted. Changes in emissions and sinks from raw material acquisition and manufacturing processes are captured to the extent that source reduction and recycling affect these processes.[2] Negative emission factors indicate that, from a waste generation

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[1] All data on recycling and compost rates are from EPA's OSW. 2005. *Municipal Solid Waste in the United States: 2003 Facts and Figures*, EPA 430-R-05-003.

[2] For reference, GHG emissions from raw materials acquisition and manufacturing are shown in column "a" of several exhibits in this chapter.

reference point, a given management practice for a particular material type results in emission reductions. However, it is important to note that none of the management-specific emission factors are to be used alone; it is the *difference* between two competing management practices that matters.

This report provides emissions and savings from several of the most common materials in MSW. For materials not explicitly covered in the previous chapters, Exhibit 8-1 presents the recommended proxy materials that readers of this report can use to calculate emissions of common materials not covered in the body of the report, including mixed metals, PVC, rubber, and textiles.

Exhibit 8-1 Recommended Surrogates for Voluntary Reporting

Material Source Reduced	Surrogate Material
Iron	Steel Cans
Other Ferrous Metals	Steel Cans
Other Nonferrous Metals	Average of Copper and Aluminum
Steel	Steel Cans
Metal (type unknown)	Average of Aluminum, Steel, and Copper
Mixed Metals (ferrous and nonferrous)	Appropriate Weighted Average
Copper	Copper Wire
Plastic (resin unknown)	Average of PET, HDPE, and LDPE
PVC/Vinyl	Average of PET, HDPE, and LDPE
Polypropylene	Average of PET, HDPE, and LDPE
Polystyrene	Average of PET, HDPE, and LDPE
Other plastic (resin known, but not 41-46)	Average of PET, HDPE, and LDPE
Rubber	Average of PET, HDPE, and LDPE
Boxboard	Corrugated Cardboard
Kraft Paper	Corrugated Cardboard
Coated Paper	Magazines/Third-class Mail
High-grade Paper	Office Paper
Paper (type unknown)	Mixed Paper – Broad Definition
Wood	Dimensional Lumber
Food	Food Discards
Organics (type unknown)	Yard Trimmings
Other Yard Waste	Yard Trimmings
Textiles	Carpet

Exhibit 8-2 shows the life-cycle GHG impacts of source reduction, presented in MTCE/ton.[3] In brief, the exhibit shows that, for all of the manufactured materials evaluated, source reduction results in GHG emission reductions. On a per-ton basis, PCs, aluminum cans, and copper wire have the greatest potential for emission reduction, due primarily to reductions in energy use in the raw material acquisition and manufacturing step.

Exhibit 8-3 shows the life-cycle GHG emissions associated with recycling. Columns (c), (d), and (e) show the GHG impacts of using recycled inputs in place of virgin inputs when the material is remanufactured. As the final column indicates, recycling results in negative emissions (measured from the point of waste generation) for all the materials considered in this analysis. GHG emission reductions associated with recycling are due to several factors, including avoided waste management emissions and reduced process energy emissions.[4] In addition, emission reductions from recycling paper products

[3] All data in these tables are presented in metric tons of carbon equivalent per short ton of waste discarded (MTCE/ton). To see these tables in $MTCO_2E$/ton, please refer to Appendix B.

[4] Process energy emissions for recycled corrugated cardboard, office paper, wood products (i.e., dimensional lumber and medium-density fiberboard), and mixed paper (broad and residential definitions) are actually higher than those for virgin production because production with recycled inputs tends to use fossil fuel-derived energy, while production with virgin inputs uses higher proportions of biomass fuel (CO_2 from such fuel is not counted in GHG

(when measured at the point of waste generation) are due in part to the forest carbon sequestration benefits of recycling paper. The materials with the greatest potential for emission reduction through recycling are aluminum cans, carpet, copper wire, and several paper grades. In addition, though the emission reductions per ton for concrete are relatively small (0.002), the enormous quantities of this material disposed of make it particularly promising as a mitigation strategy—200 million tons of waste concrete are disposed of annually in the United States.

Exhibit 8-4 presents the life-cycle GHG emissions from composting food discards, yard trimmings, and mixed organics. The exhibits show that composting these materials results in net emissions of -0.05 MTCE/ton, based on the difference between the emissions associated with transporting the materials to the composting facility and the soil carbon sequestration benefits.

Exhibit 8-5 presents the life-cycle GHG emissions from combusting each of the materials considered. This exhibit shows emissions for mass burn facilities and assumes the national average rate of ferrous recovery. Results for RDF facilities are similar. As the exhibit shows, mixed MSW combustion has net emissions of -0.03 MTCE/ton. Net GHG emissions are positive for plastics, aluminum, and glass, and negative for the other materials.

GHG emissions from landfilling each of the materials in MTCE/ton are shown in Exhibit 8-6. The values in the final column indicate that net GHG emissions from landfilling mixed MSW, under national average conditions in 2003, are positive. Among individual materials, emissions are lowest for newspaper, phonebooks, magazines/third-class mail, wood products, and yard trimmings, and highest for office paper, textbooks, and food discards.

As discussed in Chapter 6 and shown in Exhibit 6-6, the results for landfills are very sensitive to site-specific factors. Landfill gas collection practices significantly influence the net GHG emissions from landfilling the organic materials. For mixed MSW, net emissions are 0.37 MTCE/ton in landfills without landfill gas collection, and -0.09 MTCE/ton in landfills with landfill gas collection and energy recovery (see Exhibit 6-8), a difference of 0.46 MTCE to be gained by recovering and using landfill gas for electricity generation. The largest such differences attributable to landfill gas recovery are for office paper and textbooks (approximately 0.8 MTCE/ton), corrugated cardboard and mixed paper. The CH_4 oxidation rate and gas collection system efficiency also have a strong influence on the estimated net emissions for mixed waste and the organic materials. The values in Exhibit 8-6 reflect national average CH_4 recovery practices, thus the value for mixed MSW is 0.12 MTCE/ton.

Exhibit 8-7 displays the national average emissions for each management option and each material in MTCE/ton. When reviewing the emission factors, it is important to recall caveats that appear throughout this report. In particular, these estimates do not reflect site-specific variability, and they are not intended to compare one material to another from a use-phase perspective. Rather, these estimates are designed to support accounting for GHG emissions and sinks from waste management practices. A brief recap of how to apply the emission factors appears in the following section.

8.2 APPLYING GHG EMISSION FACTORS

The net GHG emission estimates presented in Exhibit 8-2 through Exhibit 8-7 (and the more detailed estimates in the preceding chapters) provide emission factors that may be used by organizations interested in quantifying and voluntarily reporting emissions reductions associated with waste management practices. In conjunction with DOE, EPA has used these estimates as the basis for developing guidance for voluntary reporting of GHG reductions, as authorized by Congress in Section 1605(b) of the Energy Policy Act of 1992. However, under the new, more rigorous 1605(b) reporting guidelines, emissions reductions from solid waste management practices must be reported separately

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inventories). In the case of dimensional lumber, production with recycled inputs requires more energy than virgin production.

Applying Emission Factors: Nonlinear Relationship between Recycling and Emission Reductions and Forest Carbon Leakage

Two caveats should be considered when applying emission factors to analyze large-scale shifts in waste management. First, increased recycling and GHG emission reductions may have a nonlinear relationship, such that emission reductions increase at a *declining rate* as recycling increases. This decline may be due to three factors: (1) energy use in manufacturing processes may be nonlinear with respect to recycled content; (2) manufacturing capacity for recycled materials may be limited in the short term, so that large-scale increases in recycling would require additional capital investment in capacity; and (3) market penetration of recyclables may have limits (e.g., due to performance characteristics), such that recyclables cannot completely replace virgin inputs in the short term.

In terms of the second caveat, the forest carbon sequestration benefits of paper and wood source reduction and recycling are based on the assumption that reduced demand for a given paper or wood product translates directly into reduced tree harvesting. Given that pulpwood and roundwood can be used for many products, some of the forest carbon sequestration benefits may be lost by an increase in harvests for these other products. This phenomenon is a form of what is sometimes termed "leakage" in the context of GHG mitigation projects.

Although both of these issues are important considerations in applying the emission factors in this report, EPA notes that the emission factors are primarily designed for use by local waste managers. The factors are intended to assess the GHG impacts of waste management decisions at a small-to-moderate scale. Readers should be cautious when applying the emission factors at a larger scale, however, since the nonlinear nature of the factors and the issue of leakage become most relevant in the larger context.

tons of office paper).[5] The emission factors developed in this report then can be used to calculate emissions under both the baseline and the alternative management practices. Once emissions for the two scenarios have been determined, the next step is to calculate the difference between the alternative scenario and the baseline scenario. The result represents the GHG emission reductions or increases attributable to the alternative waste management practice.

Exhibit 8-8 illustrates the results of this procedure in a scenario where the baseline management scenario is disposal in a landfill with national average conditions (i.e., the weighted average in terms of landfill gas recovery practice). Alternative scenarios involve source reduction, recycling, composting, or combustion. The values in the cells of the matrix are expressed in MTCE/ton and represent the *incremental change* in GHG emissions. For example, recycling 1 ton of office paper, rather than landfilling it, reduces GHG emissions by 1.31 MTCE, (see the "Recycling" columns of the exhibit). Continuing the example from the previous paragraph, if a business implements an office paper recycling program and annually diverts 10 tons of office paper (that would otherwise be landfilled) to recycling, the GHG emission reductions are:

$$10 \text{ tons/yr} \times -1.31 \text{ MTCE/ton} = -13.1 \text{ MTCE/yr}$$

Under the sign convention used in this report, the negative value indicates that emissions are reduced.

In 2003, the most recent year for which data was available, the United States recycled 30.6 percent of the MSW it produced. As part of its effort to encourage recycling, waste reduction, and GHG reduction, the EPA has set national recycling goal of 35 percent by 2008 and has proposed a goal of 40 percent by 2011. Using WARM, EPA calculated the projected incremental benefits of these goals. The current rate of 30.6 percent gave GHG benefits in 2003 of 49 MMTCE and energy benefits of 1.5

[5] The emission factors are expressed in terms of GHG emissions per ton of material managed. In the case of recycling, EPA defines 1 ton of material managed as 1 ton *collected* for recycling. As discussed in Chapter 4, the emission factors can be adjusted to calculate GHG emissions in terms of tons of recycled materials *as marketed* (reflecting losses in collection and sorting processes), or changes in the *recycled content* of products.

quadrillion Btu saved compared to a baseline of no recycling. These calculations assume landfilling 80 percent and combusting 20 percent of MSW not recycled (the national average rates). Increasing the rate to 35 percent would give GHG benefits in 2008 of 57 MMTCE and energy benefits of 1.7 quadrillion Btu saved. The benefits in 2011 of a 40 percent recycling rate would be 65 MMTCE and 1.9 quadrillion Btu.

Due to resource and data limitations, emission factors have not been developed for all material types reported by WasteWise partners, the Voluntary Reporting of GHG Program—or 1605(b) as it is commonly called—and other parties interested in reporting voluntary emission reductions. However, existing emission factors will continue to be updated and improved and new emission factors will be developed as more data become available. The latest emission factors, reflecting these ongoing revisions, can be found in WARM, EPA's waste emissions spreadsheet tool.[6]

In cases where parties have been using source reduction or recycling techniques for materials not specifically analyzed in this report, it is possible to estimate the GHG emission reductions by assigning surrogate materials. A list of materials not specifically analyzed, and their corresponding surrogates, is presented earlier in this chapter (see Exhibit 8-1). Surrogates are assigned based on consideration of similarities in characteristics likely to drive life-cycle GHG emissions, such as similarities in energy consumption during the raw material acquisition and manufacturing life-cycle stages. Note that the use of these surrogates involves considerable uncertainty.

8.3 TOOLS AND OTHER LIFE-CYCLE GHG ANALYSES

Life-cycle analysis is increasingly being used to quantify the GHG impacts of private and public sector decisions. In addition to the life-cycle analyses that underpin the emission factors in this report, Environmental Defense,[7] ICLEI, Ecobilan, and others have analyzed the life-cycle environmental impacts of various industry processes (e.g., manufacturing) and private and public sector practices (e.g., waste management). In many cases, the results of life-cycle analyses are packaged into life-cycle software tools that distill the information according to a specific user's needs.

ICF International worked with EPA to create the WARM, ReCon, and DGC tools, in addition to researching and writing this report, and creating the emission factors used here and in the tools. As mentioned earlier, the WAste Reduction Model (WARM) was designed as a tool for waste managers to weigh the GHG and energy impacts of their waste management practices. As a result, the model focuses exclusively on waste sector GHG emissions, and the methodology used to estimate emissions is consistent with international and domestic GHG accounting guidelines. Life-cycle tools designed for broader audiences necessarily include other sectors and/or other environmental impacts, and are not necessarily tied to the IPCC guidelines for GHG accounting or the methods used in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.

- WARM covers 34 types of materials and five waste management options: source reduction, recycling, combustion, composting, and landfilling. WARM accounts for upstream energy and nonenergy emissions, transportation distances to disposal and recycling facilities, carbon sequestration, and utility offsets that result from landfill gas collection and combustion. The tool provides participants in DOE's 1605(b) program with the option to report results by year, by gas, and by year and by gas (although under 1605(b)'s revised guidelines, avoided emissions from recycling must be reported separately under "other indirect emissions" and not included in the

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[6] Available at EPA's Global Warming—Waste, "Waste Reduction Model" website. Available at: http://www.epa.gov/mswclimate, then follow the link to Tools.

[7] Blum, L., Denison, R.A., and Ruston, V.F. 1997. "A Life-Cycle Approach to Purchasing and Using Environmentally Preferable Paper: A Summary of the Paper Task Force Report," *Journal of Industrial Ecology*; Volume 1; No. 3; pp, 15-46. Denison, R.A. 1996. "Environmental Life-Cycle Comparison of Recycling, Landfilling, and Incineration: A Review of Recent Studies;" *Annual Review of Energy and the Environment;* Volume 21, Chapter 6, pp.191–237.

main corporate inventory). WARM software is available free of charge in both a Web-based calculator format and a Microsoft® Excel spreadsheet. The tool is ideal for waste planners interested in tracking and reporting voluntary GHG emission reductions from waste management practices and comparing the climate change impacts of different approaches. To access the tool, visit: http://www.epa.gov/mswclimate, and follow the link to Tools. The latest version of WARM can also calculate energy savings resulting from waste management decisions.

- Recycled Content (ReCon) Tool was created by EPA to help companies and individuals estimate life-cycle GHG emissions and energy impacts from purchasing and/or manufacturing materials with varying degrees of postconsumer recycled content. The tool covers 17 material types and an analysis of baseline and alternative recycled-content scenarios. ReCon accounts for total "upstream" GHG emissions based on manufacturing processes, carbon sequestration, and avoided disposal that are related to the manufacture of the materials with recycled content. ReCon also accounts for the total energy (based on manufacturing processes and avoided disposal) related to the manufacture of materials with recycled content. The tool is ideal for companies and individuals who want to calculate GHG emissions and energy consumption associated with purchasing and manufacturing, using baseline and alternate recycled-content scenarios. To access the tool, visit: http://www.epa.gov/mswclimate, and follow the link to Tools.

- The Durable Goods Calculator (DGC) is an EPA model that enables users to calculate the GHG emission and energy implications for various disposal methods of durable goods. The model covers 14 types of durable goods and three waste management options: recycling, landfilling, and combustion. This tool functions by producing an aggregate GHG emission profile by creating a weighted average of the raw material content. The Durable Goods Calculator was developed for individuals and companies who want to make an informed decision on the GHG and energy impact they will have by disposing of durable household goods. Emission and energy estimates provided by the Durable Goods Calculator are intended to provide information regarding the GHG emission implications of waste management decisions. To access the tool, visit: http://www.epa.gov/mswclimate, and follow the link to Tools.

- The Cities for Climate Protection (CCP) campaign's GHG Emission Software was developed by Torrie Smith Associates for ICLEI (Local Governments for Sustainability). This Windows™-based tool, targeted for use by local governments, can analyze emissions and emission reductions on a community-wide basis and for municipal operations alone. The community-wide module looks at residential, commercial, and industrial buildings, transportation activity, and community-generated waste. The municipal operations module considers municipal buildings, municipal fleets, and waste from municipal in-house operations. In addition to computing GHG emissions, the CCP software estimates reductions in criteria air pollutants, changes in energy consumption, and financial costs and savings associated with energy use and other emission reduction initiatives. A version of the software program was made available for use by private businesses and institutions during the summer of 2001. CCP software subscriptions, including technical support, are available to governments participating in ICLEI. For more information, visit: www.iclei.org or contact the U.S. ICLEI office at 510–844–0699, iclei_usa@iclei.org.

- The Decision Support Tool (DST) and life-cycle inventory database for North America have been developed through funding by EPA's ORD through a cooperative agreement with the Research Triangle Institute (CR823052). The methodology is based on a multimedia, multipollutant approach and includes analysis of GHG emissions as well as a broader set of emissions (air, water, and waste) associated with MSW operations. The MSW-DST is available for site-specific applications and has been used to conduct analyses in several states and 15 communities, including use by the U.S. Navy in the Pacific Northwest. The tool is intended for use by solid waste planners at state and local levels to analyze and compare alternative MSW management

strategies with respect to cost, energy consumption, and environmental releases to the air, land, and water. The costs are based on full-cost accounting principles and account for capital and operating costs using an engineering economics analysis. The MSW-DST calculates not only projected emissions of GHGs and criteria air pollutants, but also emissions of more than 30 air- and water-borne pollutants. The DST models emissions associated with all MSW management activities, including waste collection and transportation, transfer stations, materials recovery facilities, compost facilities, landfills, combustion and refuse-derived fuel facilities, utility offsets, material offsets, and source reduction. The differences in residential, multifamily, and commercial sectors can be evaluated individually. The software has optimization capabilities that enable one to identify options that evaluate minimum costs as well as solutions that can maximize environmental benefits, including energy conservation and GHG reductions.

As of the publication of this report, RTI expects to release the database in the summer of 2006, and will be available in a Web-based version. The MSW-DST provides extensive default data for the full range of MSW process models and requires minimum input data. The defaults can be tailored to the specific communities using site-specific information. The MSW-DST also includes a calculator for source reduction and carbon sequestration using a methodology that is consistent with the IPCC in terms of the treatment of biogenic CO_2 emissions. For further information, visit RTI's website at http://www.rti.org/, and search the term "DST."

- The Tool for Environmental Analysis and Management (TEAM), developed by Ecobilan, simulates operations associated with product design, processes, and activities associated with several industrial sectors. The model considers energy consumption, material consumption, transportation, waste management, and other factors in its evaluation of environmental impacts. Many firms and some government agencies have used the model. http://www.ecobalance.com/uk_team.php.

8.4 OPPORTUNITIES FOR GHG REDUCTIONS

Although this report has focused on the five most common waste management practices—source reduction, recycling, composting, combustion, and landfilling—for select materials, future GHG quantification efforts may include a number of emerging practices:

- Co-firing waste biomass. For utilities and power generating companies with coal-fired capacity, co-firing with waste biomass may represent one of the least-cost renewable energy options. Co-firing involves replacing a portion of the coal with biomass at an existing power plant boiler. This replacement can be achieved by either mixing biomass with coal before fuel is introduced into the boiler or by using separate fuel feeds for coal and biomass. Specific biomass feedstocks include agricultural and wood waste, MSW, and industrial wastes. Given the increasing use of co-firing technology as an energy source, understanding its GHG benefits will likely be an important future EPA effort.

- Biomass pyrolysis/gasification. Pyrolysis and gasification are similar technologies in which waste is thermally decomposed in an oxygen-poor environment. In pyrolysis, organic matter is vaporized, and the vapor is condensed and collected as "bio-oil," which can then be burned for energy.[8] The advantage of pyrolysis over normal waste-to-energy incineration is that pyrolysis produces a liquid fuel that can be stored and used in a number of applications (similar to biodiesel), whereas WTE produces only electricity for immediate consumption. Biomass gasification is similar except that a gas rather than a liquid is produced.

[8] The Biomass Technology Group, "Flash Pyrolysis." Available online at: www.btgworld.com/technologies/pyrolysis.html.

- Compost as landfill cover. Using compost as landfill cover on closed landfills provides an excellent environment for the bacteria that oxidize CH_4. Under optimal conditions, compost covers can practically eliminate CH_4 emissions. Furthermore, the covers offer the possibility of controlling these emissions in a cost-effective manner. This technology is particularly promising for small landfills, where landfill gas collection is not required and the economics of landfill gas-to-energy projects are not attractive. Ancillary benefits also might arise in the compost market from this technique if using compost as a landfill cover becomes a widespread practice. An increase in composting could reduce the quantity of organic waste disposed of at MSW landfills, thereby reducing CH_4 emissions. Given the recent development of this practice, quantifying its GHG impacts will likely prove useful as landfill owners consider adopting the technology.

- Bioreactors. Bioreactors are a form of controlled landfilling with the potential to provide reliable energy generation from solid waste, as well as significant environmental and solid waste management benefits. The concept is to accelerate the decomposition process of landfill waste through controlled additions of liquid and leachate recirculation, which enhances the growth of the microbes responsible for solid waste decomposition. The result is to shorten the period of landfill gas generation, thereby rendering projections of landfill gas generation rates and yields that are much more reliable for landfill gas recovery.

- Anaerobic digestion. Several facilities are using this technique to produce CH_4 from mixed waste, which is then used to fuel energy recovery. The approach generates CH_4 more quickly and captures it more completely than in a landfill environment, and thus, from a GHG perspective, offers a potentially attractive waste management option.[9]

- The paperless office. The rise of computer technology for research, communications, and other everyday workplace functions has presented a major opportunity for source reduction in the modern office. Today's offices are commonly equipped with all the necessary technologies to bypass paper entirely and rely instead on electronic communication. This form of "comprehensive" source reduction comes with significant GHG benefits, as described in Chapter 4. Therefore, attempting to quantify and communicate these benefits to the business community will be an important task in the coming years.

- Product stewardship. More and more companies, and even entire industries, are moving toward redesigning their products to reduce their environmental footprint. By necessity, this trend involves rethinking how their products are managed at end-of-life so that valuable materials can be recovered and reused. The electronics industry is reducing the energy usage of their products as well as reducing reliance on toxic inputs in their products. They are also redesigning their products to make them easier to recycle. The packaging industry is moving towards package designs that use less material (reducing GHG emissions from transportation) and are more easily recyclable (reducing GHG emissions and energy investments in processing virgin materials). Many other industries, such as the carpet, office furniture, and textile industries, are in the process of developing sustainability standards for their products. Companies committed to this kind of change are very interested in metrics that will help them measure the environmental benefits of the changes they are making to their products.

EPA will continue to evaluate new opportunities to reduce emissions from waste management as they become known. EPA also encourages readers to consider creative approaches to waste management, particularly those with associated life-cycle energy benefits or carbon storage implications. All of the exhibits presented so far in this report have expressed GHG emissions in units of MTCE, calculated as the sum of the individual gases (CO_2, CH_4, N_2O, and PFCs) weighted by their global warming potential. In

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[9] Environment Canada. 2001. *Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions*. Submitted by ICF Consulting, Torrie-Smith Associates, and Enviros-RIS.

the Voluntary Reporting of GHG Program—also known as the 1605(b) program—established by DOE's Energy Information Administration, reporting companies are asked to provide emission reductions for each of the individual gases. In addition, the 1605(b) program requires emission reductions to be reported in the year they are achieved and does not allow participants to take credit for future emission reductions. Because the GHG emission factors presented in this report reflect the "present value" of future emissions and sinks as well as emissions and sinks occurring in the reporting year, these emission factors are not directly transferable to the 1605(b) program. For purposes of supporting the program, EPA developed a revised set of 1605(b) program emission factors that reflect emissions by gas and by year. Those emission factors provide incremental emissions for a baseline of landfilling and alternative scenarios of source reduction and recycling, although as noted above, savings calculated in this manner can no longer be directly counted under the revised 1605(b) reporting guidelines. Detailed reporting instructions and forms are available on DOE's website at:
http://www.pi.energy.gov/enhancingGHGregistry/generalguidelines.html.

Exhibit 8-2
GHG Emissions for Source Reduction (MTCE/Ton)

Material	(a) Raw Materials Acquisition and Manufacturing		(b) Forest Carbon Sequestration		(c)	(d) Net Emissions (d = a + b + c)	
	Source Reduction Displaces Current Mix of Virgin and Recycled Inputs	Source Reduction Displaces Virgin Inputs	Source Reduction Displaces Current Mix of Virgin and Recycled Inputs	Source Reduction Displaces Virgin Inputs	Waste Management Emissions	Source Reduction Displaces Current Mix of Virgin and Recycled Inputs	Source Reduction Displaces Virgin Inputs
Aluminum Cans	-2.24	-4.27	0.00	0.00	0.00	-2.24	-4.27
Steel Cans	-0.87	-1.01	0.00	0.00	0.00	-0.87	-1.01
Copper Wire	-2.00	-2.02	0.00	0.00	0.00	-2.00	-2.02
Glass	-0.16	-0.18	0.00	0.00	0.00	-0.16	-0.18
HDPE	-0.49	-0.54	0.00	0.00	0.00	-0.49	-0.54
LDPE	-0.62	-0.64	0.00	0.00	0.00	-0.62	-0.64
PET	-0.57	-0.59	0.00	0.00	0.00	-0.57	-0.59
Corrugated Cardboard	-0.24	-0.23	-1.29	-1.98	0.00	-1.52	-2.21
Magazines/Third-class Mail	-0.46	-0.46	-1.90	-1.98	0.00	-2.36	-2.44
Newspaper	-0.52	-0.58	-0.80	-1.04	0.00	-1.33	-1.62
Office Paper	-0.28	-0.28	-1.90	-1.98	0.00	-2.18	-2.26
Phonebooks	-0.68	-0.68	-1.04	-1.04	0.00	-1.72	-1.72
Textbooks	-0.60	-0.60	-1.90	-1.98	0.00	-2.50	-2.58
Dimensional Lumber	-0.05	-0.05	-0.50	-0.50	0.00	-0.55	-0.55
Medium-density Fiberboard	-0.10	-0.10	-0.50	-0.50	0.00	-0.60	-0.60
Food Discards	NA	NA	NA	NA	NA	NA	NA
Yard Trimmings	NA	NA	NA	NA	NA	NA	NA
Mixed Paper							
Broad Definition	NA	NA	NA	NA	NA	NA	NA
Residential Definition	NA	NA	NA	NA	NA	NA	NA
Office Paper Definition	NA	NA	NA	NA	NA	NA	NA
Mixed Metals	NA	NA	NA	NA	NA	NA	NA
Mixed Plastics	NA	NA	NA	NA	NA	NA	NA
Mixed Recyclables	NA	NA	NA	NA	NA	NA	NA
Mixed Organics	NA	NA	NA	NA	NA	NA	NA
Mixed MSW (as disposed)	NA	NA	NA	NA	NA	NA	NA
Carpet	-1.09	-1.09	0.00	0.00	0.00	-1.09	-1.09
Personal Computers	-15.13	-15.13	0.00	0.00	0.00	-15.13	-15.13
Clay Bricks	-0.08	-0.08	0.00	0.00	0.00	-0.08	-0.08
Concrete	NA	NA	NA	NA	NA	NA	NA
Fly Ash	NA	NA	NA	NA	NA	NA	NA
Tires	-1.09	-1.09	0.00	0.00	0.00	-1.09	-1.09

Note that totals may not add due to rounding, and more digits may be displayed than are significant.
NA: Not applicable, or in the case of composting of paper, not analyzed.

Exhibit 8-3
GHG Emissions for Recycling (MTCE/Ton)

Material	Raw Materials Acquisition and Manufacturing (RMAM)		Recycled Input Credit[a]					
	(a) RMAM Emissions Not Included in Baseline (Current Mix of Inputs)	(b) Waste Generation Baseline	(c) Process Energy	(d) Transportation Energy	(e) Process Nonenergy	(f) Forest Carbon Sequestration	(g) Waste Management Emissions	(h) (h = b+c+d+e+f+g) Net Emissions
Aluminum Cans	2.24	0.00	-2.92	-0.12	-0.66	0.00	0.00	-3.70
Steel Cans	0.87	0.00	-0.48	-0.01	0.00	0.00	0.00	-0.49
Copper Wire	2.00	0.00	-1.33	-0.02	0.00	0.00	0.00	-1.34
Glass	0.16	0.00	-0.03	0.00	-0.04	0.00	0.00	-0.08
HDPE	0.49	0.00	-0.34	0.00	-0.04	0.00	0.00	-0.38
LDPE	0.62	0.00	-0.42	0.00	-0.04	0.00	0.00	-0.46
PET	0.57	0.00	-0.40	0.00	-0.02	0.00	0.00	-0.42
Corrugated Cardboard	0.24	0.00	0.00	-0.01	0.00	-0.83	0.00	-0.85
Magazines/Third-class Mail	0.46	0.00	0.00	0.00	0.00	-0.83	0.00	-0.84
Newspaper	0.52	0.00	-0.20	-0.01	0.00	-0.55	0.00	-0.76
Office Paper	0.28	0.00	0.06	0.00	0.00	-0.83	0.00	-0.78
Phonebooks	0.68	0.00	-0.17	0.00	0.00	-0.55	0.00	-0.72
Textbooks	0.60	0.00	-0.01	0.00	0.00	-0.83	0.00	-0.85
Dimensional Lumber	0.05	0.00	0.02	0.00	0.00	-0.69	0.00	-0.67
Medium-density Fiberboard	0.10	0.00	0.01	0.00	0.00	-0.69	0.00	-0.67
Food Discards	NA	NA	NA	NA	NA	NA	NA	NA
Yard Trimmings	NA	NA	NA	NA	NA	NA	NA	NA
Mixed Paper								
Broad Definition	0.29	0.00	-0.10	-0.03	0.00	-0.83	0.00	-0.96
Residential Definition	0.29	0.00	-0.10	-0.03	0.00	-0.83	0.00	-0.96
Office Paper Definition	0.88	0.00	-0.08	-0.02	0.00	-0.83	0.00	-0.93
Mixed Metals	NA	NA	-1.20	-0.04	-0.20	0.00	NA	-1.43
Mixed Plastics	NA	NA	-0.38	0.00	-0.03	0.00	NA	-0.41
Mixed Recyclables	NA	NA	-0.11	-0.01	-0.01	0.00	NA	-0.79
Mixed Organics	NA	NA	NA	NA	NA	NA	NA	NA
Mixed MSW (as disposed)	NA	NA	NA	NA	NA	NA	NA	NA
Carpet	1.09	0.00	-1.47	-0.02	-0.47	0.00	0.00	-1.96
Personal Computers	15.13	0.00	-0.41	-0.01	-0.20	0.00	0.00	-0.62
Clay Bricks	0.08	0.00	NA	NA	NA	NA	NA	NA
Concrete	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fly Ash	NA	0.00	-0.11	0.00	-0.12	0.00	0.00	-0.24
Tires[b]	1.09	0.00	-0.50	0.00	0.00	0.00	0.00	-0.50

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[a] Material that is recycled after use is then substituted for virgin inputs in the production of new products. This credit represents the difference in emissions that results from using recycled inputs.

[a] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

Exhibit 8-4
GHG Emissions for Composting (MTCE/Ton)

Material	Raw Materials Acquisition and Manufacturing (RMAM)		(c)	(d)	(e) (e = b+c+d)
	(a) RMAM Emissions Not Included in Baseline[a]	(b) Waste Generation Baseline	Transportation to Composting	Soil Carbon Sequestration	Net Emissions (Postconsumer)
Aluminum Cans	2.24	0.00	NA	NA	NA
Steel Cans	0.87	0.00	NA	NA	NA
Copper Wire	2.00	0.00	NA	NA	NA
Glass	0.16	0.00	NA	NA	NA
HDPE	0.49	0.00	NA	NA	NA
LDPE	0.62	0.00	NA	NA	NA
PET	0.57	0.00	NA	NA	NA
Corrugated Cardboard	0.24	0.00	NA	NA	NA
Magazines/Third-class Mail	0.46	0.00	NA	NA	NA
Newspaper	0.52	0.00	NA	NA	NA
Office Paper	0.28	0.00	NA	NA	NA
Phonebooks	0.68	0.00	NA	NA	NA
Textbooks	0.60	0.00	NA	NA	NA
Dimensional Lumber	0.05	0.00	NA	NA	NA
Medium-density Fiberboard	0.10	0.00	NA	NA	NA
Food Discards	NA	0.00	0.01	-0.07	-0.05
Yard Trimmings	NA	0.00	0.01	-0.07	-0.05
Mixed Paper					
Broad Definition	0.29	0.00	NA	NA	NA
Residential Definition	0.29	0.00	NA	NA	NA
Office Paper Definition	0.88	0.00	NA	NA	NA
Mixed Metals	NA	0.00	NA	NA	NA
Mixed Plastics	NA	0.00	NA	NA	NA
Mixed Recyclables	NA	0.00	NA	NA	NA
Mixed Organics	NA	0.00	0.01	-0.07	-0.05
Mixed MSW (as disposed)	NA	NA	NA	NA	NA
Carpet	1.09	0.00	NA	NA	NA
Personal Computers	15.13	0.00	NA	NA	NA
Clay Bricks	0.08	0.00	NA	NA	NA
Concrete	NA	0.00	NA	NA	NA
Fly Ash	NA	0.00	NA	NA	NA
Tires	1.09	0.00	NA	NA	NA

Note that totals may not add due to rounding, and more digits may be displayed than are significant.
NA: Not applicable, or in the case of composting of paper, not analyzed.
[a] The value for mixed MSW is the weighted average of the RMAM emissions for those materials EPA studied.

Exhibit 8-5
GHG Emissions for Combustion (MTCE/Ton)

Values are for Mass Burn Facilities with National Average Rate of Ferrous Recovery.

Material	RMAM (a) RMAM Emissions Not Included in Baseline[a]	RMAM (b) Waste Generation Baseline	(c) Transportation to Combustion	(d) CO_2 from Combustion	(e) N_2O from Combustion	(f) Avoided Utility Emissions	(g) Ferrous Recovery	(h) (h = b+c+d+e+f+g) Net Emissions (Postconsumer)
Aluminum Cans	2.24	0.00	0.01	0.00	0.00	0.01	0.00	0.02
Steel Cans	0.87	0.00	0.01	0.00	0.00	0.01	-0.43	-0.42
Copper Wire	2.00	0.00	0.01	0.00	0.00	0.01	0.00	0.01
Glass	0.16	0.00	0.01	0.00	0.00	0.01	0.00	0.01
HDPE	0.49	0.00	0.01	0.76	0.00	-0.52	0.00	0.25
LDPE	0.62	0.00	0.01	0.76	0.00	-0.52	0.00	0.25
PET	0.57	0.00	0.01	0.56	0.00	-0.27	0.00	0.30
Corrugated Cardboard	0.24	0.00	0.01	0.00	0.01	-0.19	0.00	-0.18
Magazines/Third-class Mail	0.46	0.00	0.01	0.00	0.01	-0.15	0.00	-0.13
Newspaper	0.52	0.00	0.01	0.00	0.01	-0.22	0.00	-0.20
Office Paper	0.28	0.00	0.01	0.00	0.01	-0.19	0.00	-0.17
Phonebooks	0.68	0.00	0.01	0.00	0.01	-0.22	0.00	-0.20
Textbooks	0.60	0.00	0.01	0.00	0.01	-0.19	0.00	-0.17
Dimensional Lumber	0.05	0.00	0.01	0.00	0.01	-0.23	0.00	-0.21
Medium-density Fiberboard	0.10	0.00	0.01	0.00	0.01	-0.23	0.00	-0.21
Food Discards	NA	0.00	0.01	0.00	0.01	-0.07	0.00	-0.05
Yard Trimmings	NA	0.00	0.01	0.00	0.01	-0.08	0.00	-0.06
Mixed Paper								
Broad Definition	0.29	0.00	0.01	0.00	0.01	-0.20	0.00	-0.18
Residential Definition	0.29	0.00	0.01	0.00	0.01	-0.19	0.00	-0.18
Office Paper Definition	0.88	0.00	0.01	0.00	0.01	-0.18	0.00	-0.16
Mixed Metals	NA	0.00	0.01	0.00	0.00	0.01	-0.30	-0.29
Mixed Plastics	NA	0.00	0.01	0.68	0.00	-0.42	0.00	0.27
Mixed Recyclables	NA	0.00	0.01	0.02	0.01	-0.18	-0.01	-0.17
Mixed Organics	NA	0.00	0.01	0.00	0.01	-0.07	0.00	-0.05
Mixed MSW (as disposed)	NA	0.00	0.01	0.10	0.01	-0.14	-0.01	-0.03
Carpet	1.09	0.00	0.01	0.47	0.00	-0.37	0.00	0.11
Personal Computers	15.13	0.00	0.01	0.10	0.00	-0.04	-0.12	-0.05
Clay Bricks	0.08	0.00	0.01	NA	NA	NA	NA	0.01
Concrete	NA	0.00	NA	NA	NA	NA	NA	NA
Fly Ash	NA	0.00	NA	NA	NA	NA	NA	NA
Tires	1.09	0.00	0.01	2.05	0.00	-1.98	-0.03	0.05

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[a] The value for mixed MSW is the weighted average of the RMAM emissions for those materials EPA studied.

Exhibit 8-6
GHG Emissions for Landfilling (MTCE/Ton)[a]

Material	RMAM		(c)	(d)	(e)	(f)	(g) (g=b+c+d+e+f)
	(a) RMAM Emissions Not Included in Baseline[b]	(b) Waste Generation Baseline	Transportation to Landfill	Net Landfill CH_4	Avoided Utility Emissions	Landfill Carbon Sequestration	Net Emissions
Aluminum Cans	2.24	0.00	0.01	0.00	0.00	0.00	0.01
Steel Cans	0.87	0.00	0.01	0.00	0.00	0.00	0.01
Copper Wire	2.00	0.00	0.01	0.00	0.00	0.00	0.01
Glass	0.16	0.00	0.01	0.00	0.00	0.00	0.01
HDPE	0.49	0.00	0.01	0.00	0.00	0.00	0.01
LDPE	0.62	0.00	0.01	0.00	0.00	0.00	0.01
PET	0.57	0.00	0.01	0.00	0.00	0.00	0.01
Corrugated Cardboard	0.24	0.00	0.01	0.34	-0.02	-0.22	0.11
Magazines/Third-class Mail	0.46	0.00	0.01	0.14	-0.01	-0.22	-0.08
Newspaper	0.52	0.00	0.01	0.12	-0.01	-0.36	-0.24
Office Paper	0.28	0.00	0.01	0.60	-0.04	-0.04	0.53
Phonebooks	0.68	0.00	0.01	0.12	-0.01	-0.36	-0.24
Textbooks	0.60	0.00	0.01	0.60	-0.04	-0.04	0.53
Dimensional Lumber	0.05	0.00	0.01	0.18	-0.01	-0.31	-0.13
Medium-density Fiberboard	0.10	0.00	0.01	0.18	-0.01	-0.31	-0.13
Food Discards	NA	0.00	0.01	0.22	-0.01	-0.02	0.20
Yard Trimmings	NA	0.00	0.01	0.13	-0.01	-0.19	-0.06
Mixed Paper							
Broad Definition	0.29	0.00	0.01	0.33	-0.02	-0.22	0.09
Residential Definition	0.29	0.00	0.01	0.31	-0.02	-0.23	0.07
Office Paper Definition	0.88	0.00	0.01	0.32	-0.02	-0.18	0.13
Mixed Metals	NA	0.00	0.01	0.00	0.00	0.00	0.01
Mixed Plastics	NA	0.00	0.01	0.00	0.00	0.00	0.01
Mixed Recyclables	NA	0.00	0.01	0.26	-0.02	-0.21	0.04
Mixed Organics	NA	0.00	0.01	0.18	-0.01	-0.11	0.06
Mixed MSW (as disposed)	NA	0.00	0.01	0.29	-0.02	-0.17	0.12
Carpet	1.09	0.00	0.01	0.00	0.00	0.00	0.01
Personal Computers	15.13	0.00	0.01	0.00	0.00	0.00	0.01
Clay Bricks	0.08	0.00	0.01	0.00	0.00	0.00	0.01
Concrete	NA	0.00	0.01	0.00	0.00	0.00	0.01
Fly Ash	NA	0.00	0.01	0.00	0.00	0.00	0.01
Tires	1.09	0.00	0.01	0.00	0.00	0.00	0.01

Note that totals may not add due to rounding, and more digits may be displayed than are significant.
NA: Not applicable, or in the case of composting of paper, not analyzed.
[a] Values for landfill CH_4 and net emissions reflect projected national average CH4 recovery in year 2004.
[b] The value for mixed MSW is the weighted average of the RMAM emissions for those materials EPA studied.

Exhibit 8-7
Net GHG Emissions from Source Reduction and MSW Management Options (MTCE/Ton)

Material	Source Reduction[a]	Recycling	Composting	Combustion[b]	Landfilling[c]
Aluminum Cans	-2.24	-3.70	NA	0.02	0.01
Steel Cans	-0.87	-0.49	NA	-0.42	0.01
Copper Wire	-2.00	-1.34	NA	0.01	0.01
Glass	-0.16	-0.08	NA	0.01	0.01
HDPE	-0.49	-0.38	NA	0.25	0.01
LDPE	-0.62	-0.46	NA	0.25	0.01
PET	-0.57	-0.42	NA	0.30	0.01
Corrugated Cardboard	-1.52	-0.85	NA	-0.18	0.11
Magazines/Third-class Mail	-2.36	-0.84	NA	-0.13	-0.08
Newspaper	-1.33	-0.76	NA	-0.20	-0.24
Office Paper	-2.18	-0.78	NA	-0.17	0.53
Phonebooks	-1.72	-0.72	NA	-0.20	-0.24
Textbooks	-2.50	-0.85	NA	-0.17	0.53
Dimensional Lumber	-0.55	-0.67	NA	-0.21	-0.13
Medium-density Fiberboard	-0.60	-0.67	NA	-0.21	-0.13
Food Discards	NA	NA	-0.05	-0.05	0.20
Yard Trimmings	NA	NA	-0.05	-0.06	-0.06
Mixed Paper					
Broad Definition	NA	-0.96	NA	-0.18	0.09
Residential Definition	NA	-0.96	NA	-0.18	0.07
Office Paper Definition	NA	-0.93	NA	-0.16	0.13
Mixed Metals	NA	-1.43	NA	-0.29	0.01
Mixed Plastics	NA	-0.41	NA	0.27	0.01
Mixed Recyclables	NA	-0.79	NA	-0.17	0.04
Mixed Organics	NA	NA	-0.05	-0.05	0.06
Mixed MSW (as disposed)	NA	NA	NA	-0.03	0.12
Carpet	-1.09	-1.96	NA	0.11	0.01
Personal Computers	-15.13	-0.62	NA	-0.05	0.01
Clay Bricks	-0.08	NA	NA	NA	0.01
Concrete	NA	0.00	NA	NA	0.01
Fly Ash	NA	-0.24	NA	NA	0.01
Tires	-1.09	-0.50[d]	NA	0.05	0.01

Note that totals may not add due to rounding, and more digits may be displayed than are significant.
NA: Not applicable, or in the case of composting of paper, not analyzed.
[a] Source reduction assumes displacement of current mix of virgin and recycled inputs.
[b] Values are for mass burn facilities with a national average rate of ferrous recovery.
[c] Values reflect national average CH_4 recovery in year 2004.
[d] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

Exhibit 8-8
Net GHG Emissions of MSW Management Options Compared to Landfilling[a] (MTCE/Ton)

Material	Source Reduction Net Emissions Minus Landfilling Net Emissions: Current Mix of Inputs	Source Reduction Net Emissions Minus Landfilling Net Emissions: 100% Virgin Inputs	Recycling Net Emissions Minus Landfilling Net Emissions	Composting Net Emissions Minus Landfilling Net Emissions	Combustion[b] Net Emissions Minus Landfilling Net Emissions
Aluminum Cans	-2.26	-4.28	-3.71	NA	0.01
Steel Cans	-0.88	-1.02	-0.50	NA	-0.43
Copper Wire	-2.01	-2.03	-1.35	NA	0.00
Glass	-0.17	-0.19	-0.09	NA	0.00
HDPE	-0.50	-0.55	-0.39	NA	0.24
LDPE	-0.63	-0.65	-0.47	NA	0.24
PET	-0.58	-0.60	-0.43	NA	0.28
Corrugated Cardboard	-1.63	-2.32	-0.96	NA	-0.29
Magazines/Third-class Mail	-2.28	-2.36	-0.76	NA	-0.05
Newspaper	-1.09	-1.39	-0.52	NA	0.03
Office Paper	-2.71	-2.79	-1.31	NA	-0.70
Phonebooks	-1.49	-1.49	-0.49	NA	0.03
Textbooks	-3.03	-3.11	-1.38	NA	-0.70
Dimensional Lumber	-0.42	-0.42	-0.54	NA	-0.08
Medium-density Fiberboard	-0.47	-0.47	-0.54	NA	-0.08
Food Discards	NA	NA	NA	-0.25	-0.25
Yard Trimmings	NA	NA	NA	0.01	0.00
Mixed Paper					
Broad Definition	NA	NA	-1.06	NA	-0.27
Residential Definition	NA	NA	-1.03	NA	-0.25
Office Paper Definition	NA	NA	-1.06	NA	-0.29
Mixed Metals	NA	NA	-1.44	NA	-0.30
Mixed Plastics	NA	NA	-0.42	NA	0.26
Mixed Recyclables	NA	NA	-0.83	NA	-0.20
Mixed Organics	NA	NA	NA	-0.12	-0.12
Mixed MSW (as disposed)	NA	NA	NA	NA	-0.15
Carpet	-1.10	-1.10	-1.97	NA	0.10
Personal Computers	-15.14	-15.14	-0.63	NA	-0.06
Clay Bricks	-0.09	-0.09	-0.01	NA	-0.01
Concrete	-0.01	-0.01	-0.01	NA	-0.01
Fly Ash	-0.01	-0.01	-0.25	NA	-0.01
Tires	-1.10	-1.10	-0.51[c]	NA	0.04

Note that totals may not add due to rounding, and more digits may be displayed than are significant.
NA: Not applicable, or in the case of composting of paper, not analyzed.
[a] Values for landfilling reflect national average CH_4 recovery in year 2004.
[b] Values are for mass burn facilities with national average rate of ferrous recovery.
[c] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

* * * * *

A final note about the limitations of the GHG emission and energy consumption estimates presented in this report. EPA based its analysis on what was believed to be the best available data; where necessary, reasonable assumptions were made. The accuracy of the estimates is limited, however, by the use of these assumptions and limitations in the data sources, as discussed throughout this report. Where possible, the emission and energy factors reported here can be improved by substituting process- or site-specific data to increase the accuracy of the estimates. For example, a commercial firm with a large aluminum recycling program may have better data on the specific fuel mix of its source of aluminum and could thus calculate a more exact value for the emission factor. Despite the uncertainty in the emission and energy factors, they provide a reasonable first approximation of the GHG and energy impacts of solid waste management, and EPA believes that they provide a sound basis for evaluating voluntary actions to reduce GHG emissions and energy consumption in the waste management arena.

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APPENDIX A: GHG EMISSIONS FROM A RAW MATERIALS EXTRACTION VIEWPOINT.

The analyses conducted in the main body of this report are based on a life-cycle perspective that starts at the moment a material is discarded. EPA took this approach because expert review of the first edition indicated that the "waste-generation" approach would be more useful and comprehensible to waste managers, at whom this report is chiefly aimed. This is in contrast to a typical life-cycle analysis, which takes a "cradle-to-grave" approach. Emission factors from raw materials extraction and manufacturing perspective are presented here for those who find this viewpoint more useful.

Exhibit A-1
Net GHG Emissions from Source Reduction and MSW Management Options - Emissions Counted from a Raw Materials Extraction Reference Point (MTCE/Ton)

Material	Source Reduction[a]	Recycling[b]	Composting[b]	Combustion[b]	Landfilling[b]
Aluminum Cans	0.00	-1.46	NA	2.26	2.26
Steel Cans	0.00	0.38	NA	0.45	0.88
Copper Wire	0.00	0.66	NA	2.02	2.01
Glass	0.00	0.08	NA	0.17	0.17
HDPE	0.00	0.11	NA	0.74	0.50
LDPE	0.00	0.16	NA	0.87	0.63
PET	0.00	0.15	NA	0.87	0.58
Corrugated Cardboard	-1.29	-0.61	NA	0.06	0.34
Magazines/Third-class Mail	-1.90	-0.38	NA	0.33	0.38
Newspaper	-0.80	-0.24	NA	0.32	0.29
Office Paper	-1.90	-0.49	NA	0.11	0.81
Phonebooks	-1.04	-0.04	NA	0.48	0.44
Textbooks	-1.90	-0.25	NA	0.43	1.13
Dimensional Lumber	-0.50	-0.62	NA	-0.16	-0.08
Medium-density Fiberboard	-0.50	-0.57	NA	-0.11	-0.03
Food Discards	NA	NA	-0.05	-0.05	0.20
Yard Trimmings	NA	NA	-0.05	-0.06	-0.06
Mixed Paper					
Broad Definition	NA	-0.67	NA	0.11	0.39
Residential Definition	NA	-0.68	NA	0.11	0.36
Office Paper Definition	NA	-0.05	NA	0.72	1.01
Mixed Metals	NA	-0.16	NA	0.98	1.29
Mixed Plastics	NA	0.13	NA	0.81	0.55
Mixed Recyclables	NA	-0.41	NA	0.22	0.42
Mixed Organics	NA	NA	-0.05	-0.05	0.06
Mixed MSW as Disposed	NA	NA	NA	-0.03	0.12
Carpet	0.00	-0.87	NA	1.20	1.10
Personal Computers	0.00	14.51	NA	15.07	15.14
Clay Bricks	0.00	0.08	NA	0.08	0.09
Concrete	NA	0.00	NA	NA	0.01
Fly Ash	NA	-0.24	NA	NA	0.01
Tires	0.00	2.07[c]	NA	3.86	3.82

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[a]Source reduction assumes initial production using the current mix of virgin and recycled inputs.
[b]Includes emissions from the initial production of the material being managed, except for foodwaste, yard waste, and mixed MSW.

[c] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

Exhibit A-2
Net GHG Emissions from Source Reduction and MSW Management Options - Emissions Counted from a Raw Materials Extraction Reference Point ($MTCO_2E$/Ton)

Material	Source Reduction[a]	Recycling[b]	Composting[b]	Combustion[b]	Landfilling[b]
Aluminum Cans	0.00	-5.34	NA	8.29	8.27
Steel Cans	0.00	1.38	NA	1.64	3.21
Copper Wire	0.00	2.42	NA	7.39	7.38
Glass	0.00	0.29	NA	0.62	0.61
HDPE	0.00	0.39	NA	2.72	1.82
LDPE	0.00	0.57	NA	3.20	2.31
PET	0.00	0.56	NA	3.18	2.13
Corrugated Cardboard	-4.73	-2.25	NA	0.21	1.26
Magazines/Third-class Mail	-6.96	-1.38	NA	1.22	1.39
Newspaper	-2.95	-0.87	NA	1.18	1.06
Office Paper	-6.96	-1.81	NA	0.41	2.98
Phonebooks	-3.83	-0.16	NA	1.75	1.62
Textbooks	-6.96	-0.90	NA	1.58	4.15
Dimensional Lumber	-1.84	-2.28	NA	-0.60	-0.31
Medium-density Fiberboard	-1.84	-2.10	NA	-0.40	-0.11
Food Discards	NA	NA	-0.20	-0.18	0.72
Yard Trimmings	NA	NA	-0.20	-0.22	-0.22
Mixed Paper					
Broad Definition	NA	-2.47	NA	0.41	1.41
Residential Definition	NA	-2.48	NA	0.41	1.31
Office Paper Definition	NA	-0.17	NA	2.65	3.71
Mixed Metals	NA	-0.60	NA	3.60	4.70
Mixed Plastics	NA	0.48	NA	2.97	2.02
Mixed Recyclables	NA	-1.52	NA	0.79	1.54
Mixed Organics	NA	NA	-0.20	-0.20	0.24
Mixed MSW as Disposed	NA	NA	NA	-0.12	0.42
Carpet	0.00	-3.19	NA	4.38	4.03
Personal Computers	0.00	53.21	NA	55.27	55.51
Clay Bricks	0.00	0.28	NA	0.28	0.32
Concrete	NA	-0.01	NA	NA	0.04
Fly Ash	NA	-0.87	NA	NA	0.04
Tires	0.00	7.57[c]	NA	14.15	14.01

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[a]Source reduction assumes initial production using the current mix of virgin and recycled inputs.
[b]Includes emissions from the initial production of the material being managed, except for foodwaste, yard waste, and mixed MSW.

[c] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

APPENDIX B: CARBON DIOXIDE EQUIVALENT EMISSION FACTORS

Exhibit B-1
Net GHG Emissions from Source Reduction and MSW Management Options - Emissions Counted from a Waste Generation Reference Point ($MTCO_2E$/Ton)[a]

Material	Source Reduction[b]	Recycling	Composting[c]	Combustion[d]	Landfilling[e]
Aluminum Cans	-8.23	-13.57	NA	0.06	0.04
Steel Cans	-3.18	-1.79	NA	-1.53	0.04
Copper Wire	-7.34	-4.92	NA	0.05	0.04
Glass	-0.57	-0.28	NA	0.05	0.04
HDPE	-1.79	-1.39	NA	0.93	0.04
LDPE	-2.27	-1.69	NA	0.93	0.04
PET	-2.09	-1.54	NA	1.08	0.04
Corrugated Cardboard	-5.59	-3.11	NA	-0.65	0.40
Magazines/Third-class Mail	-8.65	-3.07	NA	-0.47	-0.30
Newspaper	-4.87	-2.79	NA	-0.74	-0.87
Office Paper	-8.00	-2.85	NA	-0.62	1.94
Phonebooks	-6.32	-2.66	NA	-0.74	-0.87
Textbooks	-9.17	-3.11	NA	-0.62	1.94
Dimensional Lumber	-2.02	-2.46	NA	-0.78	-0.49
Medium-density Fiberboard	-2.22	-2.47	NA	-0.78	-0.49
Food Discards	NA	NA	-0.20	-0.18	0.72
Yard Trimmings	NA	NA	-0.20	-0.22	-0.22
Mixed Paper					
Broad Definition	NA	-3.54	NA	-0.65	0.35
Residential Definition	NA	-3.54	NA	-0.65	0.25
Office Paper Definition	NA	-3.42	NA	-0.59	0.47
Mixed Metals	NA	-5.25	NA	-1.06	0.04
Mixed Plastics	NA	-1.49	NA	0.99	0.04
Mixed Recyclables	NA	-2.91	NA	-0.61	0.14
Mixed Organics	NA	NA	-0.20	-0.20	0.24
Mixed MSW as Disposed	NA	NA	NA	-0.12	0.42
Carpet	-3.99	-7.18	NA	0.39	0.04
Personal Computers	-55.47	-2.26	NA	-0.20	0.04
Clay Bricks	-0.28	NA	NA	NA	0.04
Concrete	NA	-0.01	NA	NA	0.04
Fly Ash	NA	-0.87	NA	NA	0.04
Tires	-3.98	-1.82[f]	NA	0.18	0.04

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.
[a]MTCE/ton: Metric tons of carbon equivalent per short ton of material. Material tonnages are on an as-managed (wet weight) basis.

[b]Source reduction assumes initial production using the current mix of virgin and recycled inputs.

[c]There is considerable uncertainty in our estimate of net GHG emissions from composting;

The values of zero are plausible values based on assumptions and a bounding analysis.

[d]Values are for mass burn facilities with national average rate of ferrous recovery.

[e]Values reflect estimated national average methane recovery in year 2004.

[f] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

Exhibit B-2
GHG Emissions of MSW Management Options Compared to Landfilling[a] ($MTCO_2E$/Ton)
(Management Option Net Emissions Minus Landfilling Net Emissions)

Material	Source Reduction[b] (Current Mix)	Source Reduction (100% Virgin Inputs)	Recycling	Composting[c]	Combustion[d]
Aluminum Cans	-8.27	-15.68	-13.61	NA	0.02
Steel Cans	-3.21	-3.73	-1.83	NA	-1.57
Copper Wire	-7.38	-7.44	-4.96	NA	0.02
Glass	-0.61	-0.68	-0.32	NA	0.01
HDPE	-1.82	-2.00	-1.43	NA	0.89
LDPE	-2.31	-2.39	-1.73	NA	0.89
PET	-2.13	-2.19	-1.58	NA	1.04
Corrugated Cardboard	-5.99	-8.49	-3.51	NA	-1.05
Magazines/Third-class Mail	-8.35	-8.65	-2.77	NA	-0.17
Newspaper	-4.01	-5.09	-1.92	NA	0.13
Office Paper	-9.94	-10.23	-4.79	NA	-2.57
Phonebooks	-5.45	-5.45	-1.79	NA	0.13
Textbooks	-11.11	-11.41	-5.05	NA	-2.57
Dimensional Lumber	-1.53	NA	-1.97	NA	-0.29
Medium-density Fiberboard	-1.73	NA	-1.98	NA	-0.29
Food Discards	NA	NA	NA	-0.92	-0.90
Yard Trimmings	NA	NA	NA	0.02	0.00
Mixed Paper					
Broad Definition	NA	NA	-3.89	NA	-1.00
Residential Definition	NA	NA	-3.79	NA	-0.90
Office Paper Definition	NA	NA	-3.88	NA	-1.06
Mixed Metals	NA	NA	-5.29	NA	-1.10
Mixed Plastics	NA	NA	-1.53	NA	0.95
Mixed Recyclables	NA	NA	-3.05	NA	-0.75
Mixed Organics	NA	NA	NA	-0.43	-0.43
Mixed MSW as Disposed	NA	NA	NA	NA	-0.55
Carpet	-4.03	-4.03	-7.22	NA	0.35
Personal Computers	-55.51	-55.51	-2.30	NA	-0.24
Clay Bricks	-0.32	-0.32	-0.04	NA	-0.04
Concrete	-0.04	-0.04	-0.05	NA	-0.04
Fly Ash	-0.04	-0.04	-0.91	NA	-0.04
Tires	-4.02	-4.02	-1.86[e]	NA	0.14

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

[a]Values for landfilling reflect projected national average methane recovery in year 2004.

[b]Source reduction assumes initial production using the current mix of virgin and recycled inputs.

[c]Calculation is based on assuming zero net emissions for composting.

[d]Values are for mass burn facilities with national average rate of ferrous recovery.

[e] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

Exhibit B-3
GHG Emissions for Source Reduction (MTCO2E/Ton of Material Source Reduced)
Emissions Measured from a Waste Generation Reference Point[a]

Material	(a) Raw Materials Acquisition and Manufacturing		(b) Forest Carbon Sequestration		(c)	(d) Net Emissions (d = a + b + c)	
	Source Reduction Displaces Current Mix of Virgin and Recycled Inputs	Source Reduction Displaces Virgin Inputs	Source Reduction Displaces Current Mix of Virgin and Recycled Inputs	Source Reduction Displaces Virgin Inputs	Waste Management Emissions	Source Reduction Displaces Current Mix of Virgin and Recycled Inputs	Source Reduction Displaces Virgin Inputs
Aluminum Cans	-8.23	-15.64	0.00	0.00	0.00	-8.23	-15.64
Steel Cans	-3.18	-3.69	0.00	0.00	0.00	-3.18	-3.69
Copper Wire	-7.34	-7.40	0.00	0.00	0.00	-7.34	-7.40
Glass	-0.57	-0.65	0.00	0.00	0.00	-0.57	-0.65
HDPE	-1.79	-1.97	0.00	0.00	0.00	-1.79	-1.97
LDPE	-2.27	-2.35	0.00	0.00	0.00	-2.27	-2.35
PET	-2.09	-2.15	0.00	0.00	0.00	-2.09	-2.15
Corrugated Cardboard	-0.86	-0.83	-4.73	-7.26	0.00	-5.59	-8.09
Magazines/Third-class Mail	-1.69	-1.69	-6.96	-7.26	0.00	-8.65	-8.95
Newspaper	-1.92	-2.12	-2.95	-3.83	0.00	-4.87	-5.95
Office Paper	-1.04	-1.02	-6.96	-7.26	0.00	-8.00	-8.28
Phonebooks	-2.49	-2.49	-3.83	-3.83	0.00	-6.32	-6.32
Textbooks	-2.20	-2.21	-6.96	-7.26	0.00	-9.17	-9.47
Dimensional Lumber	-0.18	-0.18	-1.84	-1.84	0.00	-2.02	-2.02
Medium-density Fiberboard	-0.37	-0.37	-1.84	-1.84	0.00	-2.22	-2.22
Food Discards	NA	NA	NA	NA	NA	NA	NA
Yard Trimmings	NA	NA	NA	NA	NA	NA	NA
Mixed Paper							
Broad Definition	NA	NA	NA	NA	NA	NA	NA
Residential Definition	NA	NA	NA	NA	NA	NA	NA
Office Paper Definition	NA	NA	NA	NA	NA	NA	NA
Mixed Plastics	NA	NA	NA	NA	0.00	NA	NA
Mixed Recyclables	NA	NA	NA	NA	0.00	NA	NA
Mixed Organics	NA	NA	NA	NA	0.00	NA	NA
Mixed MSW (as disposed)	NA	NA	NA	NA	NA	NA	NA
Carpet	-3.99	-3.99	0.00	0.00	0.00	-3.99	-3.99
Personal Computers	-55.47	-55.47	0.00	0.00	0.00	-55.47	-55.47
Clay Bricks	-0.28	-0.28	0.00	0.00	0.00	-0.28	-0.28
Concrete	NA	NA	NA	NA	NA	NA	NA
Fly Ash	NA	NA	NA	NA	NA	NA	NA
Tires	-13.97	-13.97	0.00	0.00	0.00	-13.97	-13.97

Note that totals may not add due to rounding and more digits may be displayed than are significant.
NA: Not applicable, or in the case of composting of paper, not analyzed.
[a] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

Exhibit B-4
Recycling (GHG Emissions in MTCO2E/Ton)
Emissions Measured from a Waste Generation Reference Point[a]

	Raw Materials Acquisition and Manufacturing (RMAM)		Recycled Input Credit[b]					
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h) (h = b+c+d+e+f+g)
Material	RMAM Emissions Not Included in Baseline (Current Mix of Inputs)	Waste Generation Baseline	Process Energy	Transportation Energy	Process Non-Energy	Forest Carbon Sequestration	Waste Management Emissions	Net Emissions
Aluminum Cans	8.23	0.00	-10.70	-0.44	-2.43	0.00	0.00	-13.57
Steel Cans	3.18	0.00	-1.75	-0.04	0.00	0.00	0.00	-1.79
Copper Wire	7.34	0.00	-4.86	-0.06	0.00	0.00	0.00	-4.92
Glass	0.57	0.00	-0.12	-0.02	-0.14	0.00	0.00	-0.28
HDPE	1.79	0.00	-1.25	0.00	-0.15	0.00	0.00	-1.39
LDPE	2.27	0.00	-1.55	0.00	-0.15	0.00	0.00	-1.69
PET	2.09	0.00	-1.46	0.00	-0.08	0.00	0.00	-1.54
Corrugated Cardboard	0.86	0.00	0.00	-0.05	-0.01	-3.06	0.00	-3.11
Magazines/Third-class Mail	1.69	0.00	-0.01	0.00	0.00	-3.06	0.00	-3.07
Newspaper	1.92	0.00	-0.75	-0.03	0.00	-2.02	0.00	-2.79
Office Paper	1.04	0.00	0.22	0.00	-0.02	-3.06	0.00	-2.85
Phonebooks	2.49	0.00	-0.64	0.00	0.00	-2.02	0.00	-2.66
Textbooks	2.20	0.00	-0.05	0.00	0.00	-3.06	0.00	-3.11
Dimensional Lumber	0.18	0.00	0.07	0.01	0.00	-2.53	0.00	-2.46
Medium-density Fiberboard	0.37	0.00	0.05	0.01	0.00	-2.53	0.00	-2.47
Food Discards	NA	0.00	NA	NA	NA	NA	NA	NA
Yard Trimmings	NA	0.00	NA	NA	NA	NA	NA	NA
Mixed Paper								
Broad Definition	1.06	0.00	-0.37	-0.11	-0.01	-3.06	0.00	-3.54
Residential Definition	1.06	0.00	-0.37	-0.11	-0.01	-3.06	0.00	-3.54
Office Paper Definition	3.24	0.00	-0.29	-0.07	0.00	-3.06	0.00	-3.42
Mixed Metals	NA	0.00	-4.38	-0.16	-0.71	0.00	0.00	-5.25
Mixed Plastics	NA	0.00	-1.38	0.00	-0.12	0.00	0.00	-1.49
Mixed Recyclables	NA	0.00	-0.40	-0.04	-0.05	-2.42	0.00	-2.91
Mixed Organics	NA	NA	NA	NA	NA	NA	NA	NA
Mixed MSW (as disposed)	NA	NA	NA	NA	NA	NA	NA	NA
Carpet	3.99	0.00	-5.38	-0.06	-1.74	0.00	0.00	-7.18
Personal Computers	55.47	0.00	-1.49	-0.04	-0.73	0.00	0.00	-2.26
Clay Bricks	0.28	0.00	NA	NA	NA	NA	NA	NA
Concrete	NA	0.00	0.00	-0.01	0.00	0.00	0.00	-0.01
Fly Ash	NA	0.00	-0.42	0.00	-0.45	0.00	0.00	-0.87
Tires[c]	13.97	0.00	-6.40	0.00	0.00	0.00	0.00	-6.40

Note that totals may not add due to rounding and more digits may be displayed than are significant.
NA: Not applicable, or in the case of composting of paper, not analyzed.
[a] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).
[b] Material that is recycled after use is then substituted for virgin inputs in the production of new products. This credit represents the difference in emissions that results from using recycled inputs
[c] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

Exhibit B-5
Composting (GHG Emissions in MTCO2E/Ton)
Values are for Mass Burn Facilities with National Average Rate of Ferrous Recovery. Emissions Measured from a Waste Generation Reference Point[a]

Material	Raw Materials Acquisition and Manufacturing (RMAM)		(c)	(d)	(e) (e = b+c+d)
	(a) RMAM Emissions Not Included in Baseline[b]	(b) Waste Generation Baseline	Transportation to Composting	Soil Carbon Sequestration	Net Emissions (Post-Consumer)
Aluminum Cans	-8.23	0.00	NA	NA	NA
Steel Cans	-3.18	0.00	NA	NA	NA
Copper Wire	-7.34	0.00	NA	NA	NA
Glass	-0.57	0.00	NA	NA	NA
HDPE	-1.79	0.00	NA	NA	NA
LDPE	-2.27	0.00	NA	NA	NA
PET	-2.09	0.00	NA	NA	NA
Corrugated Cardboard	-0.86	0.00	NA	NA	NA
Magazines/Third-class Mail	-1.69	0.00	NA	NA	NA
Newspaper	-1.92	0.00	NA	NA	NA
Office Paper	-1.04	0.00	NA	NA	NA
Phonebooks	-2.49	0.00	NA	NA	NA
Textbooks	-2.20	0.00	NA	NA	NA
Dimensional Lumber	-0.18	0.00	NA	NA	NA
Medium-density Fiberboard	-0.37	0.00	NA	NA	NA
Food Discards	NA	0.00	0.04	-0.24	-0.20
Yard Trimmings	NA	0.00	0.04	-0.24	-0.20
Mixed Paper					
Broad Definition	1.06	0.00	NA	NA	NA
Residential Definition	1.06	0.00	NA	NA	NA
Office Paper Definition	3.24	0.00	NA	NA	NA
Mixed Metals	NA	0.00	NA	NA	NA
Mixed Plastics	NA	0.00	NA	NA	NA
Mixed Recyclables	NA	0.00	NA	NA	NA
Mixed Organics	NA	0.00	0.04	-0.24	-0.20
Mixed MSW (as disposed)	NA	NA	NA	NA	NA
Carpet	-3.99	0.00	NA	NA	NA
Personal Computers	-55.47	0.00	NA	NA	NA
Clay Bricks	-0.28	0.00	NA	NA	NA
Concrete	NA	0.00	NA	NA	NA
Fly Ash	NA	0.00	NA	NA	NA
Tires	-13.97	0.00	NA	NA	NA

Note that totals may not add due to rounding and more digits may be displayed than are significant.
NA: Not applicable, or in the case of composting of paper, not analyzed.
[a] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

Exhibit B-6
Combustion (GHG Emissions in MTCO2E/Ton)
Values are for Mass Burn Facilities with National Average Rate of Ferrous Recovery. Emissions Measured from a Waste Generation Reference Point[a]

Material	Raw Materials Acquisition and Manufacturing (RMAM)		(c)	(d)	(e)	(f)	(g)	(h) (h = b+c+d+e+f+g)
	(a) RMAM Emissions Not Included in Baseline[b]	(b) Waste Generation Baseline	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Avoided Utility Emissions	Ferrous Recovery	Net Emissions (Postconsumer)
Aluminum Cans	-8.23	0.00	0.03	0.00	0.00	0.03	0.00	0.06
Steel Cans	-3.18	0.00	0.03	0.00	0.00	0.02	-1.58	-1.53
Copper Wire	-7.34	0.00	0.03	0.00	0.00	0.03	0.00	0.05
Glass	-0.57	0.00	0.03	0.00	0.00	0.02	0.00	0.05
HDPE	-1.79	0.00	0.03	2.79	0.00	-1.89	0.00	0.93
LDPE	-2.27	0.00	0.03	2.79	0.00	-1.89	0.00	0.93
PET	-2.09	0.00	0.03	2.04	0.00	-0.98	0.00	1.08
Corrugated Cardboard	-0.86	0.00	0.03	0.00	0.04	-0.71	0.00	-0.65
Magazines/Third-class Mail	-1.69	0.00	0.03	0.00	0.04	-0.53	0.00	-0.47
Newspaper	-1.92	0.00	0.03	0.00	0.04	-0.81	0.00	-0.74
Office Paper	-1.04	0.00	0.03	0.00	0.04	-0.69	0.00	-0.62
Phonebooks	-2.49	0.00	0.03	0.00	0.04	-0.81	0.00	-0.74
Textbooks	-2.20	0.00	0.03	0.00	0.04	-0.69	0.00	-0.62
Dimensional Lumber	-0.18	0.00	0.03	0.00	0.04	-0.84	0.00	-0.78
Medium-density Fiberboard	-0.37	0.00	0.03	0.00	0.04	-0.84	0.00	-0.78
Food Discards	NA	0.00	0.03	0.00	0.04	-0.24	0.00	-0.18
Yard Trimmings	NA	0.00	0.03	0.00	0.04	-0.28	0.00	-0.22
Mixed Paper								
Broad Definition	1.06	0.00	0.03	0.00	0.04	-0.72	0.00	-0.65
Residential Definition	1.06	0.00	0.03	0.00	0.04	-0.71	0.00	-0.65
Office Paper Definition	3.24	0.00	0.03	0.00	0.04	-0.66	0.00	-0.59
Mixed Metals	NA	0.00	0.03	0.00	0.00	0.02	-1.12	-1.06
Mixed Plastics	NA	0.00	0.03	2.49	0.00	-1.53	0.00	0.99
Mixed Recyclables	NA	0.00	0.03	0.06	0.03	-0.67	-0.05	-0.61
Mixed Organics	NA	0.00	0.03	0.00	0.04	-0.26	0.00	-0.20
Mixed MSW (as disposed)	NA	0.00	0.03	0.37	0.04	-0.51	-0.05	-0.12
Carpet	-3.99	0.00	0.03	1.72	0.00	-1.36	0.00	0.39
Personal Computers	-55.47	0.00	0.03	0.38	0.00	-0.16	-0.45	-0.20
Clay Bricks	-0.28	0.00	0.03	NA	NA	NA	NA	0.03
Concrete	NA	0.00	NA	NA	NA	NA	NA	NA
Fly Ash	NA	0.00	NA	NA	NA	NA	NA	NA
Tires	-13.97	0.00	0.03	7.53	0.00	-7.25	-0.13	0.18

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

[a] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

Exhibit B-7
Landfilling (GHG Emissions in MTCO2E/Ton)
Values for Landfill Methane and Net Emissions Reflect Projected National Average Methane Recovery in year 2003.
Emissions Measured from a Waste Generation Reference Point[a]

Material	Raw Materials Acquisition and Manufacturing (RMAM)		(c)	(d)	(e)	(f)	(g) (g=b+c+d+e+f)
	(a)	(b)					
	RMAM Emissions Not Included in Baseline[b]	Waste Generation Baseline	Transportation to Landfill	Net Landfill CH_4	Avoided Utility Emissions	Landfill Carbon Sequestration	Net Emissions
Aluminum Cans	8.23	0.00	0.04	0.00	0.00	0.00	0.04
Steel Cans	3.18	0.00	0.04	0.00	0.00	0.00	0.04
Glass	7.34	0.00	0.04	0.00	0.00	0.00	0.04
Copper Wire	0.57	0.00	0.04	0.00	0.00	0.00	0.04
HDPE	1.79	0.00	0.04	0.00	0.00	0.00	0.04
LDPE	2.27	0.00	0.04	0.00	0.00	0.00	0.04
PET	2.09	0.00	0.04	0.00	0.00	0.00	0.04
Corrugated Cardboard	0.86	0.00	0.04	1.26	-0.08	-0.82	0.40
Magazines/Third-class Mail	1.69	0.00	0.04	0.51	-0.03	-0.82	-0.30
Newspaper	1.92	0.00	0.04	0.45	-0.03	-1.33	-0.87
Office Paper	1.04	0.00	0.04	2.20	-0.13	-0.16	1.94
Phonebooks	2.49	0.00	0.04	0.45	-0.03	-1.33	-0.87
Textbooks	2.20	0.00	0.04	2.20	-0.13	-0.16	1.94
Dimensional Lumber	0.18	0.00	0.04	0.65	-0.04	-1.14	-0.49
Medium-density Fiberboard	0.37	0.00	0.04	0.65	-0.04	-1.14	-0.49
Food Discards	NA	0.00	0.04	0.82	-0.05	-0.08	0.72
Yard Trimmings	NA	0.00	0.04	0.48	-0.03	-0.71	-0.22
Mixed Paper	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Broad Definition	1.06	0.00	0.04	1.19	-0.07	-0.81	0.35
Residential Definition	1.06	0.00	0.04	1.13	-0.07	-0.84	0.25
Office Paper Definition	3.24	0.00	0.04	1.18	-0.07	-0.67	0.47
Mixed Metals	NA	0.00	0.04	0.00	0.00	0.00	0.04
Mixed Plastics	NA	0.00	0.04	0.00	0.00	0.00	0.04
Mixed Recyclables	NA	0.00	0.04	0.94	-0.06	-0.78	0.14
Mixed Organics	NA	0.00	0.04	0.64	-0.04	-0.41	0.24
Mixed MSW (as disposed)	NA	0.00	0.04	1.06	-0.07	-0.61	0.42
Carpet	3.99	0.00	0.04	0.00	0.00	0.00	0.04
Personal Computers	55.47	0.00	0.04	0.00	0.00	0.00	0.04
Clay Bricks	0.28	0.00	0.04	0.00	0.00	0.00	0.04
Concrete	NA	0.00	0.04	0.00	0.00	0.00	0.04
Fly Ash	NA	0.00	0.04	0.00	0.00	0.00	0.04
Tires	13.97	0.00	0.04	0.00	0.00	0.00	0.04

Note that totals may not add due to rounding and more digits may be displayed than are significant.
NA: Not applicable, or in the case of composting of paper, not analyzed.
[a] Under the accounting convention used in this analysis, emissions are quantified from a waste generation reference point (once the material has already undergone the raw materials acquisition and manufacturing phase).

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APPENDIX C: ROADMAP FROM THE SECOND EDITION

Since the release of the second edition of the report, numerous adjustments and improvements have been made to the underlying data and methodology supporting the life-cycle emission factors. This new edition of the report has incorporated these updates, and the improvements are also reflected in the latest versions of the WAste Reduction Model (WARM), Recycled Content (ReCon) Tool and Durable Goods Calculator (DGC).[1] This appendix provides a brief explanation of the changes made to the underlying data and provides details on the latest emission factors being used in this edition of the report. Additional details on these changes can be found in the body of this report.

The primary changes and improvements to the life-cycle analysis since the 2002 report include the following:

- Developed emission factors for eight new material types: copper wire, clay bricks, concrete, fly ash, tires, carpet, personal computers, and mixed metals. As information on these additional material types became available, the list of material types has been expanded to provide greater capture of the municipal solid waste stream.
- Updated the national average fuel mix for utility-generated electricity based on information from the DOE, EIA, *Annual Energy Review: 2004* on electric utility consumption of fossil fuels.
- Incorporated new energy data into calculations of utility offsets;
- Updated the characterization of the municipal waste stream based on the 2003 *Municipal Solid Waste in the United States: Facts and Figures* report. This characterization study is used to develop emission factors for several of the "mixed" material types (e.g., mixed metals, mixed MSW).
- Revised the "current mix" values for virgin and recycled content of materials based on data obtained from Franklin Associates Ltd.
- Incorporated open loop recycling of corrugated cardboard and mixed paper into the life-cycle methodology. This provides a more accurate picture of the recycling of these materials such that recycled corrugated cardboard does not always go into the production of new corrugated cardboard.
- Added retail transportation (factory to point-of-sale) to the methodology utilizing commodity transportation data from the U.S. Census Bureau.
- Updated data on the behavior of organic materials in the landfill environment based on recent studies by Dr. Barlaz of NC State University.
- Updated information on landfill gas recovery rates to reflect latest values from the U.S. Inventory of Greenhouse Gas Emissions and Sinks;
- Updated the forest carbon sequestration factors based on revised estimates from the U.S. Department of Agriculture—Forest Service.

It should be noted that the fundamental aspects of the methodology reported in the 2002 report remain unchanged and this appendix is designed to communicate changes in the GHG emission factors that have occurred since the publication of the 2002 report.

The following pages present tables showing the net emission factors presented in the 2002 report, in order for readers to see how they have changed. Because numerous factors have been updated,

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[1] Available online at http://yosemite.epa.gov/oar/globalwarming.nsf/content/ActionsWaste.html, under the "tools" heading.

including the average fuel mix and forest carbon sequestration values, all emission factors for source reduction, recycling, combustion, and landfilling presented in the tables below have changes; however, in some cases the change may not be apparent, due to rounding. The emission factors for composting have not changed.

Exhibit C-1 presents the net emission factors for source reduction from the 2002 report, as well as the components used to generate the net emission factors.

Exhibit C-2 presents the net emission factors for recycling from the 2002 report, as well as the components used to generate the net emission factors. In addition to the general changes outlined at the beginning of the Appendix, the benefits of recycling aluminum have been revised. The process energy values were updated to incorporate revised fuel mix data for the production of aluminum sheet and transportation energy values were also updated based on energy data obtained from a personal computer life-cycle analysis performed by Franklin Associates Ltd. The process non-energy values were revised to incorporate additional anode production data provided by Franklin Associates Ltd. along with the latest data on perfluorocarbon emission characteristics for aluminum smelting.

Exhibit C-3 presents the net emission factors for composting yard trimmings from the 2002 report, as well as the components used to generate the net emission factors. Although compost emission factors were developed for grass, leaves and branches, and new columns were added to the summary table to accommodate potential CO2 and CH4 emissions from composting, these changes had no impact on the net emission factors.

Exhibit C-4 presents the net emission factors for combustion from the 2002 report, as well as the components used to generate the net emission factors.

Exhibit C-5 presents the net emission factors for landfilling from the 2002 report, as well as the components used to generate the net emission factors. The total carbon sequestration factors for coated paper, newsprint, leaves and grass and the landfill CH_4 yields for corrugated cardboard, office paper, food discards, and branches were updated based on methodology changes suggested by Dr. Mort Barlaz of NCSU.

Exhibit C-1

GHG Emissions for Source Reduction
(MTCE/Ton of Material Source Reduced)

Material	Avoided GHG Emissions from Raw Materials Acquistion and Manufacturing		Post-consumer	Changes in Forest Carbon Storage		Net Emissions	Net Emissions
	For Current Mix of Inputs	For 100% Virgin Inputs		For Current Mix of Inputs	For 100% Virgin Inputs	For Current Mix of Inputs	For 100% Virgin Inputs
Aluminum Cans	-2.49	-4.67	0.00	0.00	0.00	-2.49	-4.67
Steel Cans	-0.79	-1.01	0.00	0.00	0.00	-0.79	-1.01
Glass	-0.14	-0.16	0.00	0.00	0.00	-0.14	-0.16
HDPE	-0.49	-0.53	0.00	0.00	0.00	-0.49	-0.53
LDPE	-0.61	-0.64	0.00	0.00	0.00	-0.61	-0.64
PET	-0.49	-0.58	0.00	0.00	0.00	-0.49	-0.58
Corrugated Cardboard	-0.24	-0.22	0.00	-0.28	-0.73	-0.51	-0.96
Magazines/Third-class Mail	-0.46	-0.46	0.00	-0.58	-0.73	-1.04	-1.19
Newspaper	-0.46	-0.59	0.00	-0.35	-0.73	-0.81	-1.32
Office Paper	-0.31	-0.28	0.00	-0.50	-0.73	-0.80	-1.01
Phonebooks	-0.64	-0.67	0.00	-0.65	-0.73	-1.28	-1.40
Textbooks	-0.59	-0.59	0.00	-0.64	-0.73	-1.23	-1.32
Dimensional Lumber	-0.05	-0.05	0.00	-0.50	-0.50	-0.55	-0.55
Medium-density Fiberboard	-0.10	-0.10	0.00	-0.50	-0.50	-0.60	-0.60
Mixed Paper							
Broad Definition	NA	NA	NA	NA	NA	NA	NA
Residential Definition	NA	NA	NA	NA	NA	NA	NA
Office Paper Definition	NA	NA	NA	NA	NA	NA	NA
Mixed MSW	NA	NA	NA	NA	NA	NA	NA

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

NA: Not applicable, or in the case of composting of paper, not analyzed.

Exhibit C-2

GHG Emissions for Recycling
(MTCE/Ton of Material Recovered)

(a) Material	(b) Recycled Input Credit*: Process Energy	(c) Recycled Input Credit*: Transportation Energy	(d) Recycled Input Credit*: Process Non-Energy	(e) Forest Carbon Sequestration	(f) (f = b + c + d + e) GHG Reductions From Using Recycled Inputs Instead of Virgin Inputs
Aluminum Cans	-2.92	-0.14	-1.05	0.00	-4.11
Steel Cans	-0.48	-0.01	0.00	0.00	-0.49
Glass	-0.03	0.00	-0.04	0.00	-0.08
HDPE	-0.34	0.00	-0.04	0.00	-0.38
LDPE	-0.43	0.00	-0.04	0.00	-0.47
PET	-0.40	0.00	-0.02	0.00	-0.42
Corrugated Cardboard	0.04	-0.01	0.00	-0.73	-0.71
Magazines/Third-class Mail	0.00	0.00	0.00	-0.73	-0.74
Newspaper	-0.21	-0.01	0.00	-0.73	-0.95
Office Paper	0.06	0.00	0.00	-0.73	-0.68
Phonebooks	-0.18	0.00	0.00	-0.73	-0.91
Textbooks	-0.01	0.00	0.00	-0.73	-0.75
Dimensional Lumber	0.02	0.00	0.00	-0.69	-0.67
Medium-density Fiberboard	0.01	0.00	0.00	-0.69	-0.67
Mixed Paper					
Broad Definition	0.08	-0.02	0.00	-0.73	-0.67
Residential Definition	0.08	-0.02	0.00	-0.73	-0.67
Office Paper Definition	-0.08	-0.02	0.00	-0.73	-0.83

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

*Material that is recycled after use is then substituted for virgin inputs in the production of new products. This credit represents the difference in emissions that results from using recycled inputs rather than virgin inputs. The credit accounts for loss rates in collection, processing, and remanufacturing. Recycling credit is based on a weighted average of closed- and open-loop recycling for mixed paper. All other estimates are for closed-loop recycling.

Exhibit C-3

Net GHG Emissions from Composting
(In MTCE Per Short Ton of Yard Trimmings Composted)

Emission/ Storage Factor (for 2010)					
Soil Carbon Restoration			Increased Humus Formation	Transportation Emissions	Net Carbon Flux
Unweighted	Proportion of C that is not passive	Weighted estimate			
-0.04	48%	-0.02	-0.05	0.01	-0.05

Exhibit C-4

Gross Emissions of GHGs from MSW Combustion (MTCE/Ton)

(a) Material Combusted	(b) Combustion CO_2 Emissions From Non-Biomass Per Ton Combusted	(c) Combustion N_2O Emissions Per Ton Combusted	(d) Transportation CO_2 Emissions Per Ton Combusted	(e) (e = b + c + d) Gross GHG Emissions Per Ton Combusted
Aluminum Cans	0.00	0.00	0.01	0.01
Steel Cans	0.00	0.00	0.01	0.01
Glass	0.00	0.00	0.01	0.01
HDPE	0.76	0.00	0.01	0.77
LDPE	0.76	0.00	0.01	0.77
PET	0.56	0.00	0.01	0.56
Corrugated Cardboard	0.00	0.01	0.01	0.02
Magazines/Third-class Mail	0.00	0.01	0.01	0.02
Newspaper	0.00	0.01	0.01	0.02
Office Paper	0.00	0.01	0.01	0.02
Phonebooks	0.00	0.01	0.01	0.02
Textbooks	0.00	0.01	0.01	0.02
Dimensional Lumber	0.00	0.01	0.01	0.02
Medium-density Fiberboard	0.00	0.01	0.01	0.02
Food Discards	0.00	0.01	0.01	0.02
Yard Trimmings	0.00	0.01	0.01	0.02
Mixed MSW	0.10	0.01	0.01	0.12
Carpet	0.47	0.00	0.01	0.48
Personal Computers	0.75	0.00	0.01	0.76

Note that totals may not add due to rounding, and more digits may be displayed than are significant.
Note that Exhibits 6-1, 6-2, and 6-5 show coated paper but not mixed paper;
mixed paper is shown in the summary exhibit (Exhibit 6-6).
The summary values for mixed paper are based on the proportions of the four paper types (newspaper, office paper, corrugated cardboard, and coated paper) that comprise the different "mixed paper" definitions.
The values for phone books and textbooks are proxies, based on newspaper and office paper, respectively.

Exhibit C-5
Net GHG Emissions from Landfilling

(a)	(b) Net GHG Emissions from CH_4 Generation (MTCE/Wet Ton)				(c)	(d)	(e) (e = b + c + d) Net GHG Emissions from Landfilling (MTCE/Wet Ton)			
Material	Landfills Without LFG Recovery	Landfills With LFG Recovery and Flaring	Landfills With LFG Recovery and Electric Generation	Year 2000 National Average	Net Carbon Storage (MTCE/Wet Ton)	GHG Emissions From Transportation (MTCE/Wet Ton)	Landfills Without LFG Recovery	Landfills With LFG Recovery and Flaring	Landfills With LFG Recovery and Electric Generation	Year 2000 National Average
Aluminum Cans	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Steel Cans	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Glass	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
HDPE	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
LDPE	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
PET	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Corrugated Cardboard	0.48	0.12	0.06	0.29	-0.22	0.01	0.27	-0.09	-0.15	0.08
Magazines/Third-class Mail	0.26	0.07	0.03	0.16	-0.29	0.01	-0.02	-0.21	-0.25	-0.12
Newspaper	0.23	0.06	0.03	0.14	-0.36	0.01	-0.12	-0.29	-0.32	-0.21
Office Paper	1.09	0.27	0.14	0.66	-0.04	0.01	1.05	0.24	0.10	0.62
Phonebooks	0.23	0.06	0.03	0.14	-0.36	0.01	-0.12	-0.29	-0.32	-0.21
Textbooks	1.09	0.27	0.14	0.66	-0.04	0.01	1.05	0.24	0.10	0.62
Dimensional Lumber	0.15	0.04	0.02	0.09	-0.21	0.01	-0.04	-0.16	-0.18	-0.10
Medium-density Fiberboard	0.15	0.04	0.02	0.09	-0.21	0.01	-0.04	-0.16	-0.18	-0.10
Food Discards	0.30	0.08	0.04	0.18	-0.02	0.01	0.29	0.06	0.03	0.17
Yard Trimmings	0.17	0.04	0.02	0.10	-0.21	0.01	-0.03	-0.15	-0.18	-0.09
Grass	0.19	0.05	0.02	0.12	-0.12	0.01	0.09	-0.06	-0.08	0.01
Leaves	0.15	0.04	0.02	0.09	-0.39	0.01	-0.23	-0.34	-0.36	-0.29
Branches	0.15	0.04	0.02	0.09	-0.21	0.01	-0.04	-0.16	-0.18	-0.10
Mixed Paper										
Broad Definition	0.53	0.13	0.07	0.32	-0.23	0.01	0.31	-0.08	-0.15	0.10
Residential Definition	0.49	0.12	0.06	0.29	-0.24	0.01	0.26	-0.10	-0.16	0.07
Office Paper Definition	0.58	0.15	0.07	0.35	-0.21	0.01	0.38	-0.05	-0.12	0.15
Mixed MSW	0.26	0.06	0.03	0.16	-0.10	0.01	0.17	-0.02	-0.06	0.07

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

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